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WASHINGTON STATE
DEPARTMENT OF
ECOLOGY

TIMBER/FISH
& WILDLIFE

EFFECTIVENESS OF WASHINGTON'S FOREST PRACTICE RIPARIAN MANAGEMENT ZONE REGULATIONS FOR PROTECTION OF STREAM TEMPERATURE

Prepared for
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ABSTRACT

The Forest Practices Rules and Regulations contain Best Management Practices **(BMP)** which include requirements for Ripatian Management Zones **(RMZ)** on certain water types affected by timber harvest activities. The purpose of this study was to test the effectiveness of the **BMPs** (i.e., **RMZs)** at achieving water quality standards for temperature.

Recording thermographs were deployed upstream and downstream of thiin **RMZs** statewide during the summer of 1990 to monitor stream temperature response to timber harvests. Streams and riparian zones were characterized to **evaluate** factors influencing the observed temperature conditions.

Maximum observed water temperatures ranged from **12.8°C** to **19.9°C.** Maximum water temperature change between upstream and downstream monitoring sites ranged from **0.3°C** to **5.2°C.** Definitive determinations of whether applicable water quality criteria were met or exceeded were not possible for many of the study sites due to uncertainties related to thermograph accuracy and/or representativeness of the monitoring period. Water temperature criteria were met or judged likely to be met at three of the thiin study sites. These **RMZs** were considered effective. Temperature conditions at five of the thiin study sites exceeded applicable criteria for **maximum** allowable temperature, with conditions at an additional three sites possibly exceeding criteria. The BMP was considered ineffective at six of the sites where maximum temperature criteria were exceeded or possibly exceeded. At two of the five sites where maximum allowable temperature criteria were exceeded, the exceedances were attributed to factors other than timber harvesting at the study site, and the BMP was considered effective. Possible exceedance of the criteria for **allowable** temperature change due to timber harvesting was indicated by the monitoring results at two of 13 sites. At one additional site, exceedance of the temperature change criteria was suspected based on spot field checks.

The primary factors influencing BMP effectiveness appear to be site elevation, post-harvest shade levels, groundwater flux within the reach, and stream morphology. Stream modification by beavers was a significant factor influencing the effectiveness of **RMZs** at some sites. The proposed new **TFW method** for identifying temperature sensitive streams takes the most important factors into account, and is expected to correctly identify streams where enhanced **RMZs** are needed in a majority of cases. To optimize the effectiveness of **RMZs,** procedures to identify and address site specific anomalies which result in temperature sensitivities that would not be identified by the new **TFW** stream temperature screen and/or model should be incorporated into the **BMPs.**

ACKNOWLEDGEMENTS

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The project would not have been possible without the participation of numerous TFW cooperators. The following organizations and individuals provided Best Management Practices (BMP) implementation study sites and logistical support for the study: Boise Cascade Corporation, Champion International Corporation, Colville Confederated Tribes, Mr. Ron Nixon, Omak Wood Products, Inc., SDS Lumber Company, Simpson Timber Company, and Weyerhaeuser Company. The following persons provided the authors valuable help in deployment of thermographs: Deborah Cornett, Bob Penhale, Cathy Rajala, and Joanne Schuett-Hames. Much of the information used in this project would not have been available without the efforts of Andy Carlson and the Department of Wildlife. Thanks to Jean Caldwell, Kent Doughty, Kate Sullivan, and John Tooley of the TFW Temperature Work Group for their insights and advice on various aspects of the study. And finally, thanks to Kent Doughty, Fred Greef, Mark Hicks, Steve Holaday, Will Kendra, and Art Larson for their review of the draft report, and to Barbara Tovrea for preparing the final document.

METRIC TO ENGLISH CONVERSION FACTORS

Multiply Metric Units	By	To Obtain English Units
Meters (m)	3.28	Feet
Kilometers (km)	0.621	Miles
Hectares (ha)	2.471	Acres
Liters/second (L/s)	0.0353	Cubic feet/ second (cfs)

Degrees Celsius to Degrees Fahrenheit: °F = (°C)(1.8)+32

INTRODUCTION

The potential effects of timber harvest on stream temperature were identified as a major concern to be addressed by the Timber/Fish/Wildlife (TFW) Water Quality Steering Committee of the Cooperative Monitoring, Evaluation, and Research Committee (CMER). Within the Washington Forest Practices Rules and Regulations (Chapter 222-30 WAC), the riparian management zone (RMZ) rules were established as Best Management Practices (BMPs) to protect larger, fish-bearing, type l-3 streams (generally 3rd or&r or greater) from adverse temperature increases. Riparian management zones are essentially streamside buffers left as a part of timber harvesting practices on state and private land in Washington. The Forest Practice Rules define an RMZ as "a specified area alongside Type 1, 2, and 3 Waters where specific measures are taken to protect water quality and fish and wildlife habitat."

The RMZ rules specify standard prescriptions for buffer strip widths and leave tree requirements along streams. RMZs are intended to provide adequate shading to maintain suitable water temperatures, as well as provide wildlife and fish habitat and protect the physical integrity of the streams. The rules require alternative harvest plans which retain greater amounts of shading where streams are found to be temperature sensitive according to a method acceptable to the Department of Natural Resources. Where it is demonstrated that significant adverse water temperature impacts from proposed harvests are expected following the standard RMZ prescriptions, the rules require that 50% to 75% of the preharvest shade be retained. A copy of the RMZ rules evaluated is included in Appendix A.

The Temperature Work Group (TWG) of CMER undertook a study to characterize stream temperature regimes in Washington and develop a method to be used in applying the temperature sensitivity provisions of the Forest Practice Rules (Sullivan, *et.* al. 1990). During the summer of 1988, stream temperature data was collected from 92 sites throughout the state for an analysis of stream temperature regimes. More comprehensive data was collected at 33 of the sites to evaluate the predictive capabilities of existing reach and basin temperature models. Study sites included type l-3 streams located in all forested ecoregions of the state. representing a variety of riparian shading conditions ranging from mature conifer forest to sites completely devoid of shade. With the exception of one site, this study did not use data from areas where timber harvesting had been conducted in accordance with current RMZ rules because field studies were conducted before these rules were implemented.

This extensive data collection and analysis effort culminated in the development of a method for use by forest managers and regulatory agencies for'predicting temperature sensitivity and designing RMZs. The method provides a means of identifying sites which require greater temperature protection than standard RMZ prescriptions provide. Tools developed for the method include a temperature screen and a computer model. The screen is a nomograph used for placing the stream of interest into one of three temperature categories based on site elevation and the amount of stream shading. The model incorporates additional site information to predict expected stream temperature based on existing and proposed shade levels. As of this writing, the method developed by the TWG is undergoing field implementation and sensitivity testing, and the Forest Practice Rules are being revised to incorporate use of the new method.

Although the aforementioned temperature study did include a preliminary evaluation of the effectiveness of the RMZ rules based on empirical relationships, it was not specifically designed to test BMP effectiveness. The main focus of the present study is to determine, through field monitoring, the effectiveness of the RMZ rules when applied in actual forest management situations. The test of BMP (i.e., RMZ) effectiveness is their ability to meet state water quality standards for stream temperature.

The water quality standards for surface waters in the State of Washington (Chapter 173-201 WAC) establish the beneficial uses of waters and incorporate specific numeric and narrative criteria for parameters such as water temperature. These criteria are intended to define the level of protection necessary to fully support the beneficial uses. The water quality standards regulation includes two types of temperature criteria applicable to forest streams: 1) an absolute maximum temperature not to be exceeded, and 2) a maximum allowable incremental increase in temperature that may be caused by nonpoint source activities (i.e. forest practices). The standards provide for different classifications of surface waters depending on water quality potential and beneficial uses to be protected. Streams subject to the RMZ provisions of the Forest Practices Rules are either Class A or AA. (The actual classification is based on the provisions found in CH 173-201-070 and 080 WAC, and is generally determined by whether the waterbody is within the drainage basin of a lake or a stream which has been specifically designated Class AA.) Both Class A and AA streams are designated for the protection of all aquatic life uses, including salmonid spawning, rearing, and migration.

Water quality criteria for temperature that apply to streams affected by forest management activities are described below. For Class AA streams, the maximum allowable temperature is 16.3°C, except where exceeded by natural conditions. Incremental temperature increases caused by any nonpoint source activity (such as timber harvesting) may not exceed 2.8°C. Where natural conditions exceed 16.0°C, increases due to human activities are limited to 0.3°C. (In other words, the allowable incremental increase ranges from 0.3 to 2.8°C depending on natural background conditions.) For Class A streams, the maximum allowable temperature is 18.3°C, except where exceeded by natural conditions. Incremental increases due to nonpoint source activities may not exceed 2.8°C, except that where natural conditions exceed 18.0°C increases caused by human activity may not exceed 0.3°C. In order for the BMPs to be considered effective, both the criteria for maximum temperature and incremental increase in temperature must be met.

Study Objectives

The objectives of the study were:

1) Determine the effectiveness of the BMPs (i.e. the RMZ rules) at maintaining water temperatures at levels which meet the criteria for maximum allowable temperature established in state water quality standards.

2) Determine the effectiveness of the BMPs at meeting water quality criteria pertaining to incremental increases in temperature.

3) Evaluate the influence of various stream and riparian zone characteristics on BMP effectiveness.

This study of BMP effectiveness did not evaluate temperature conditions in smaller, type 4 and 5 waters (generally first or second order streams) affected by timber harvesting activities. However, the water quality standards and criteria discussed in the previous section apply to all surface waters of the state, including streams that do not bear fish. The criteria are intended to protect all aquatic life in streams. In many cases, the smaller type 5 streams do not have surface flow during, the summer, so criteria would apply when they are flowing. This study therefore, should be viewed as a limited evaluation of evaluating BMP effectiveness, as it addresses only those fish-bearing streams covered by the RMZ rules.

METHODS

The overall approach to achieving the study objectives was to evaluate stream temperature conditions within representative RMZs that had been designed in compliance with post-TFW Forest Practice Rules for timber harvesting. An upstream/downstream monitoring approach was used. Each RMZ studied serves as an example of BMP implementation. Results from study RMZs are evaluated individually as a series of case studies to determine BMP effectiveness and collectively to evaluate factors contributing to effectiveness or ineffectiveness of the BMPs.

Site Selection Criteria

Representative study sites were selected using a Department of Wildlife database on RMZ characteristics (Carlson, 1991). The Department of Wildlife database contains information on riparian zone and stream channel characteristics collected during field surveys. Criteria for candidate study sites included: representative examples of both east side and west side RMZ prescriptions, examples of both 1 and 2 sided RMZs, units harvested in accordance with RMZ rules (as given in Washington Forest Practices Rules and Regulations, November 1, 1988), road access within a reasonable distance of monitoring sites, and where possible, RMZ lengths of at least 600 meters. RMZs representing a wide range of elevation and canopy cover were selected. RMZs along water type 2 and 3 streams were generally used, since larger streams are less influenced by riparian shading (Sullivan, *et.al.* 1990). An exception was the South Fork of Deep Creek which is a type 1 stream.

Streams with relatively mature riparian canopy cover (i.e. second growth timber stands) upstream from the study RMZ were given preference, since these areas would more closely represent natural background conditions. RMZs along stream reaches without tributaries were chosen because it was desirable to have minimal change in flow within the study reach. After an initial screening using the Department of Wildlife database, reconnaissance visits were made to prospective study sites to verify their suitability. Since units were approved for harvest under RMZ rules, it was assumed that the BMP was properly adhered to unless obvious discrepancies were noted during field reconnaissance. Sites which did not appear to be in compliance with RMZ rules were excluded from monitoring.

Water type, as defined in the Forest Practices Rules and Regulations, is one of the determinants of RMZ requirements. In general, water type is inversely related to stream order. For the study sites, this was taken from the Department of Natural Resources water type maps attached to the Forest Practice Applications. The water quality standards classification of monitored streams was determined by examining the drainage network in relation to the criteria for surface water classifications given in CH 173-201-070 and 080 WAC.

Field Methods

Temuerature

Temperature data was collected using Unidata® data loggers and temperature probes (thermistors). For consistency, individual data loggers and two-thermistor probe sets were paired throughout the study. Each data logger and probe set combination is referred to as a thermograph.

Thermographs were calibrated prior to initial deployment, and again at the conclusion of the study, in order to document instrument bias and performance at representative temperatures. At the completion of monitoring, the raw data was adjusted for instrument bias based on the before- and after-calibration results. A certified reference thermometer (ERTCO® Instrument number 1326) was used for calibration. As a field check on the instruments, air and water temperatures were taken using a hand held thermometer at all thermograph sites at the time of deployment and retrieval.

Each thermograph had two thermistors, one sensing air temperature and the other water temperature. Thermographs were programmed to record maximum, minimum, and average air and water temperature on an hourly basis, based on thermistor readings which were scanned every five seconds. The thermistorsequilibrate very rapidly to changing temperatures, and have a maximum response time of less than one minute for a 54°C temperature change, according to the manufacturer (Barney, 1992). Thermographs were deployed concurrently just upstream of the RMZ boundary to monitor background conditions, and in the downstream portion of the RMZ to record the temperature response of the study reach.

Both the air and water temperature probes were positioned so as to be shaded from direct sunlight. The air temperature probes were placed approximately one meter above the ground near (but not directly over) the stream channel. The water temperature probes were placed in a representative stream cross-section, generally within the main current (thalweg), avoiding back-eddies and backwater areas. The upstream and downstream water temperature probes were placed at similar depths and channel conditions. Water temperature probes were placed deep enough to minimize the influence of streamflow fluctuations. Total water depth at the location of the probe and depth to the thermistor were recorded at the time of installation and removal of'the thermograph.

Thermographs were generally left in place for two weeks at each study site. Deployment of thermographs began during the third week of July 1990 and continued through late September, 1990. It was preferable to conduct monitoring during the mid-July to mid-August period when the highest air temperatures generally occur. However, limitations on equipment and personnel did not allow monitoring of a sufficient number of sites during this period, and deployment of thermographs continued with the hope that late season high temperatures would be representative of critical summer conditions. For sites monitored after August 15, daily temperature data from representative National Oceanic and Atmospheric Administration (NOAA) weather stations were used to evaluate the extent to which the monitored period represented the summer high temperatures.

Discharge

Stream discharge was estimated at both upstream and downstream thermograph sites, eitber at the time of thermograph deployment or retrieval. In some cases, discharge readings were taken at both times. Current velocity measurements were obtained using a Marsh-McBirney® flow meter at multiple points at each cross-section. Upstream and downstream measurements were taken on the same day, as close in time as practicable, and were compared to provide a rough estimate of streamflow gain or loss over the monitored reach. At one of the study sites, discharge readings were not taken, but a rough (order of magnitude) visual estimate was made in order to facilitate comparison. At another site, a discharge measurement was obtained at the downstream site only.

RMZ Leneth

RMZ length is the distance from the upstream boundary of the harvest unit to the downstream thermograph site. In most cases, these distances were measured along the stream course using a string box or measuring tape. In the case of Tokul Creek and Tributary to Pioneer Creek, the distance was estimated from aerial photography and topographic maps using a map wheel.

Riparian Shade Level

The level of shade provided by the riparian canopy over a stream is a primary factor influencing stream temperature (Sullivan, et al. 1990). A spherical densiometer was used to determine the percentage shade above the stream channel at the upstream and downstream thermograph sites. Densiometer readings were taken in four directions (facing downstream, right bank, upstream, and left bank) and then averaged.

Average riparian shading for the monitored RMZ reach was determined by taking the mean of the Department of Wildlife measurements taken within the monitored reach plus the measurement made at the downstream study site. The Department of Wildlife measurements were made by the same densiometer method at 76-meter intervals along the stream course. The Department of Wildlife shade measurements were made during the summer of 1989 for our west side sites, and during the summer of 1990 for our east side study sites. Average riparian shading was not determined for an extended reach above the RMZ; only the shade at the upstream thermograph site was measured.

Other Characteristics of Study Sites

In addition to data collected in the field, available information on other site characteristics was obtained. The influence of various site factors was considered in evaluating BMP effectiveness. These factors are discussed site by site in the case summaries presented in the following section. In the discussion section, site characteristics are evaluated by grouping the sites into categories of effectiveness and comparing site attributes within and between the categories. A principle components analysis was used to further explore the relationships between site characteristics, temperature parameters, and BMP effectiveness. Simple linear regression was also used to examine correlations between temperature parameters and site characteristics.

Stream Gradient

The gradient (in percent) for each stream reach between the upstream and downstream thermograph sites was estimated using elevations obtained from USGS topographic maps.

Distance from Divide

This is the distance from the upstream RMZ boundary, measured along the main stream channel, to the watershed divide. In the headwater portion of the watershed, the tributary with the greatest distance to divide is measured. Distance from divide was estimated from USGS topographic maps using a map wheel.

Elevation

Elevation is determined at the RMZ midpoint and at the upstream and downstream monitoring sites, as interpreted from USGS topographic maps.

Stream Depth

Average bankfull depth is the mean of the Department of Wildlife stream depth measurements made within the monitored reach, at intervals of 76 meters along the stream course. These measurements were taken from the plane of the ordinary high water mark (Washington State Department of Wildlife, 1990). In addition to average bankfull depth, actual water depth was measured at the thermistor location (generally in the thalweg) at the time of thermograph deployment and retrieval.

Averaee Bankfull Stream Width

Average bankfull width is the mean of the Department of Wildlife measurements of stream width made within the monitored reach, as measured between ordinary high water marks at intervals of 76 meters along the stream course.

Stream Azimuth

Stream azimuth was determined using USGS topographic maps. It is the true azimuth of the generalized stream course, taken along a lime drawn between the upstream and downstream monitoring sites.

RMZ Width

RMZ width is the mean width within the study reach. For two-sided RMZs, it is the mean width per side of the stream. This was determined from the Department of Wildlife database by taking the average of RMZ width measurements made at 76-meter intervals. The average width of the entire RMZ may be different from the average width within the study reach. RMZ width measurements made by the Department of Wildlife essentially represent the width of the leave tree perimeter, delimited by the ordiiary high water mark and the apparent edge of the clearcut or partial cut harvest unit. This may differ from width of the regulatory RMZ, which has certain restrictions on equipment use, timber felling, etc., and which may or may not contain leave trees.

Tree Count Information

The Department of Wildlife database was used to obtain an estimate of the average number of standing trees $\geq$ 10 centimeters diameter at breast height (DBH) per hectare withii the study RMZs. The relative proportion of conifer and deciduous species was determined. The database was also used to estimate the average total number of trees per hectare. This is reported as average total stems per hectare, and includes all tree species that are at least 1.4 meters in height, regardless of diameter. All tree data was extrapolated from macro-plots surveyed by the Department of Wildlife at 76-meter intervals along the stream course.

The database was also used to evaluate whether any trees were harvested within the RMZ, based on the presence of recent (less than five years old) stumps within the sample plots. For the purposes of this assessment, harvesting within the RMZ refers to removal of merchantable size trees from within the apparent leave tree perimeter. This perimeter marks the apparent boundary between the RMZ (as delimited in Department of Wildlife surveys) and the adjacent clearcut or partial cut harvest unit. Our determination of whether harvesting occurred within the RMZ. does not necessarily indicate whether trees were harvested within the regulatory RMZ. In fact, all or most trees could be felled within a portion of an RMZ beyond the leave tree perimeter as long as certain restrictions on equipment use, etc. were adhered to. The Department of Wildlife survey does not allow for a definitive determination of harvesting within the RMZ except in cases where a substantial amount of harvesting occurred. Observations made during site visits were used in conjunction with the database to draw general conclusions about whether there was harvesting within the RMZ.

Determination of BMP Effectiveness

The case summaries presented in the following section include a determination of whether water quality criteria were exceeded, which is the primary test of whether or not the RMZ is effective at achieving water quality standards. This determination is based on evaluation of the monitoring results in consideration of: 1) the accuracy of the monitoring instruments, and 2) whether or not the monitored period is representative of critical water temperature regimes (i.e. conditions associated with maximum water temperature increases).

Instrument Accuracy

Regarding the first consideration, the thermographs used are considered accurate to within $\pm 0.5°C$ for the purposes of this study. This is based on the manufacturer's accuracy and resolution specifications (Unidata Australia, 1990) and field experience with the equipment.

Representativeness of Monitorine Period

To determine whether the monitored period is representative of critical temperature regimes, air temperature records from representative NOAA weather stations were examined for those sites not monitored between July 15 and August 15. Stations were chosen in consideration of overall proximity to the study site, elevation, and climate region. The highest two-day mean of daily maximum air temperatures that occurred during the dates the stream in question was monitored was compared to the highest two-day mean that occurred at the same weather station during the July 15 to August 15 period for 1990. If the highest two-day mean occurring during the monitoring period is greater than 3°C below the highest two-day mean for July 15-August 15, 1990, then the monitored period is not considered representative of critical temperature regimes.

Another important consideration in evaluating late season monitoring results is the solar angle (i.e. degrees above the horizon) relative to that which occurs in mid-summer. This was evaluated using a solar ephemeris (Currier, 1980) to determine the approximate deviation from the mid-summer, mid-day solar angle for certain late season sites. The midday solar angle has been related to average net solar radiation (in terms of heat flux) by Brown (1970). Net solar radiation influences the potential magnitude of stream heating.

Maximum Equilibrium Temperature

The determination that monitoring results are not representative of critical temperature conditions is equivalent to saying that the stream reach did not reach maximum equilibrium temperature during the monitoring period. The concept of maximum equilibrium temperature refers to the maximum annual temperature that would occur given the site conditions unique to a particular thermal reach, and is explained in Sullivan et *al.* (1990). When the maximum equilibrium temperature is reached, increased heat inputs to the stream are balanced with heat loss through evaporation and other processes. Once this point is reached, stream temperature would not be expected to increase further even though higher air temperatures may occur. Thus, it is possible to monitor critical stream temperature conditions at times when air temperatures are below the annual maximum.

The maximum equilibrium temperature of a particular stream may be determined by examining plots of summertime air and water temperature to identify the water temperature "ceiling" that is not exceeded with fluctuations in maximum daily air temperature. While equilibrium conditions are apparent on some of our late season thermograph plots, we believe that the equilibrium could be shifted higher during midsummer due to higher solar angles and substantially higher air temperatures. Therefore, we chose to use the conservative assumption that critical conditions were not reached if air temperatures were more than 3°C below the annual maximum for sites monitored after August 15. It is possible that some of the streams we indicate were not monitored during critical conditions may in fact have reached their maximum equilibrium temperature. However, since we have no data on midsummer water temperatures ***in these streams, we*** cannot be certain that ***apparent*** equilibrium temperatures we observed correspond to the ***maximum*** equilibrium temperatures.

Levels of Certainty

In some cases our data clearly indicate that temperature criterion were exceeded. These are cases where criteria are exceeded by > 0.5°C (the accuracy of the thermographs). In other cases, it is clear that certain criteria are met, such as where the RMZ or another factor such as groundwater inflow appears to have a cooling effect on the stream relative to upstream conditions.

However, due to the two considerations discussed above, a definitive determination of whether or not a water quality criterion has been exceeded is not possible for many of our study sites. Sites where a definitive determination is not possible due to uncertainties regarding instrument performance were judged to represent a "possible" exceedance for the purposes of this assessment. These include sites where the observed water temperatures were within $\pm 0.5°C$ of the applicable criteria, or within $1.0°C$ where the monitoring period was not representative of critical temperature regimes. We consider the BMP to be ineffective when such possible exceedances can be attributed to forest practices.

Other sites were judged as "unlikely" to exceed criteria because, although the monitoring period was not representative of critical temperatures regimes, certain site factors lead to the expectation that criteria would be met even under critical conditions. Based on a review of temperature graphs presented in the data appendix to Sullivan *et* al. (1990), we would not expect a maximum temperature difference of more than 4 to 6°C between late July and late September in streams with at least a moderate amount of shading. We consider the BMP to be effective in cases where exceedances are "unlikely". And finally, there are sites where, due to the time of monitoring and the marginal nature of the results, no conclusions can be made regarding water quality standards compliance.

An additional consideration when evaluating compliance with the criteria for allowable incremental temperature change due to nonpoint source activities is the concept of natural background temperature. In a sense, this represents what the forest manager designing the RMZ has as a baseline from which to measure performance of the RMZ. Ideally, the baseline from which to measure the incremental change associated with timber harvesting would be the temperature conditions that existed within the RMZ reach before harvesting. An alternative to using a before/after study design, which would require at least two summers of monitoring, is to use the upstream/downstream approach employed in this study. With the upstream/downstream approach, we assume that the upstream monitoring site can serve as a baseline against which the stream's response to the RMZ can be evaluated. We believe this assumption is valid so long as the two sites are in close proximity to each other and the upstream and downstream reaches are similar in terms of stream morphology, hydrology, and pre-harvest riparian vegetation.

In this study, the upstream and downstream sites were in close proximity to each other, such that any differences in elevation, stream orientation, etc., are minor and would not affect stream temperature regimes. In most cases, we believe that stream and riparian characteristics of the upstream reach are appropriate to serve as a baseline for evaluating the incremental increase associated with the RMZ. However, in four cases there are differences in stream or riparian characteristics that make the upstream results unsuitable as a baseline for evaluating incremental increases in temperature. These situations are discussed in the case summaries.

In this study, the background temperature is that measured at the upstream edge of the RMZ. The background temperature is considered equivalent to "natural background" if the streamside area for at least a few hundred meters upstream is covered in relatively mature standing timber, even though it may be a second-growth stand.

RESULTS

A total of thirteen RMZs were monitored, including nine established according to west side RMZ regulations and four established according to east side regulations. One additional east side RMZ was originally included in the study, but no useful data were collected at this site due to a data logger malfunction. The study site locations are shown in Figure 1, overlaid on a map of ecoregions as given in Omemik (1987). Maps of the individual study sites showing the harvest units overlaid on topography are presented in Appendii B.

The case summaries that follow provide descriptions of the RMZs studied and summarize monitoring results. Results and study site descriptors are also presented in Tables 1, 2, and 3. Line graphs of temperature monitoring results are presented opposite each case summary. These include hourly maximum air and water temperature and the water temperature differential between the upstream and downstream monitoring sites. The water temperature differential is based on comparisons of the average hourly water temperatures (downstream minus upstream). Review of hourly temperature data shows that average hourly water temperature closely tracks the maximum hourly water temperature. For air temperature, however, the maximum hourly values are sometimes slightly higher than hourly average values. The applicable water quality criteria are plotted on the line graphs of water temperature results. For the water temperature differential, the criteria is either 0.3°C or 2.8°C, depending on the water temperature of the upstream site which is assumed to represent baseline conditions unless otherwise noted in the case summaries.

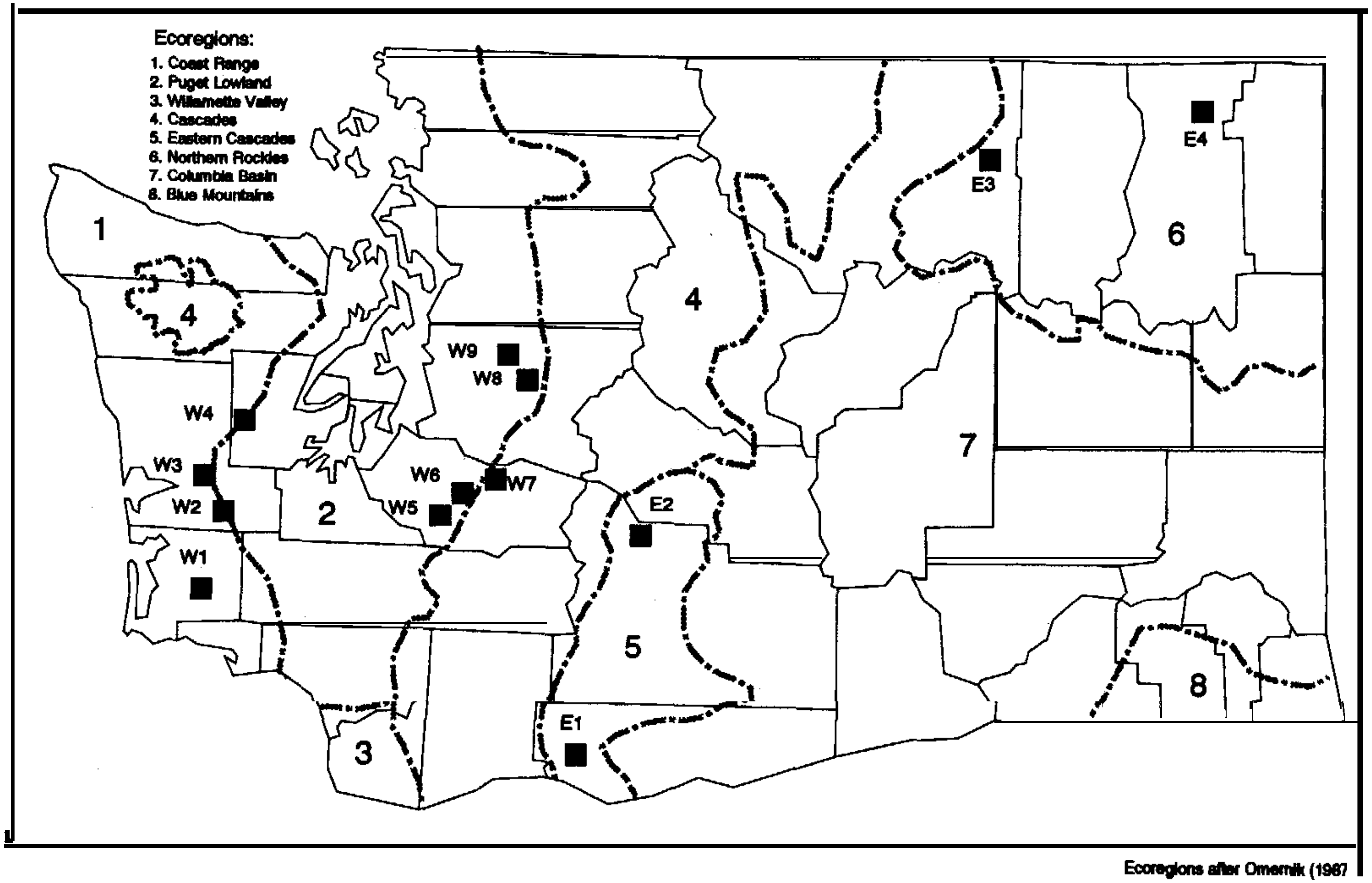


Figure 1: Distribution of Study Sites by Ecoregion

TABLE 1: TEMPERATURE BMP EVALUATION RESULTS SUMMARY

RMZ IDENTIFICATION	STREAM NAME	MONITORING DATES	WATER TYPE	WATER QUALITY CLASS	ELEVATION @ RMZ MIDPOINT (METERS)	AVERAGE RMZ SHADE (%)	DAILY MAXIMUM AIR TEMP. (CELSIUS)	MEDIAN OF DAILY MAX. AIR TEMP. (CELSIUS)	DAILY MAXIMUM WATER TEMP. (CELSIUS)	MEDIAN OF DAILY MAX. WATER TEMP. (CELSIUS)	MAXIMUM DAILY WATER TEMP. DIFFERENTIAL (IN CELSIUS)	MEDIAN OF MAX. DAILY WATER TEMP. DIFFERENTIAL (IN CELSIUS)	EXCEEDS WQ CRITERIA? MAXIMUM ALLOWABLE TEMPERATURE	EXCEEDS WQ CRITERIA? ALLOWABLE TEMPERATURE CHANGE	BMP CONSIDERED EFFECTIVE?
W1	TRIBUTARY	9/13 to	2	A	100	95					-0.1 to 0.6	0.1	UNLIKELY	NO	YES
DOWNSTREAM	TO TRAP CREEK	9/29					15.3-26.3	19.9	12.5-13.6	12.7					
UPSTREAM							15.2-32.5	24.1	12.8-13.9	13.1					
W2	TRIBUTARY TO	7/19 to	3	A	175	67					NO DATA		POSSIBLY	SUSPECTED	NO
DOWNSTREAM	PIONEER CREEK	8/7					16.1-39.7	28.8	14.3-18.2	16.9					
UPSTREAM							NO DATA		NO DATA						
W3	BLACK CREEK	7/18 to	3	A	80	52					0.9 to 1.6	1.4	YES	UNKNOWN	NO
DOWNSTREAM		7/31					17.6-40.9	29.1	15.6-19.9	18.6					
UPSTREAM							16.8-37.6	24.7	14.7-19.1	17.6					
W4	NORTH FORK	8/15	3	AA	185	91					2.7 to 5.2	4.6	YES	UNKNOWN	NO
DOWNSTREAM	RABBIT CREEK	to 8/30					17.6-27.8	22.0	16.3-19.3	18.3					
UPSTREAM							16.6-26.6	21.0	13.6-14.6	14.0					
W5	SOUTH FORK	8/24 to	3	AA	425	82					0.3 to 1.9	1.1	POSSIBLY	POSSIBLY	NO
DOWNSTREAM	OHOP CREEK	9/12					14.4-28.5	19.9	13.2-15.9	13.8					
UPSTREAM							14.7-25.1	19.2	12.4-14.4	13.3					
W6	BEAR CREEK	8/31 to	3	A	465	37					1.4 to 2.8	2.2	POSSIBLY	UNKNOWN	NO
DOWNSTREAM		9/21					14.5-26.7	21.1	14.1-17.5	15.6					
UPSTREAM							14.4-29.8	22.2	12.9-14.9	13.6					
W7	NEW POND CREEK	9/21 to	3	A	610	77					0.9 to 1.2	0.9	UNLIKELY	UNLIKELY	YES
DOWNSTREAM		10/9					10.9-22.6	16.8	9.6-13.4	12.1					
UPSTREAM							10.9-22.2	16.5	8.9-13.1	11.5					
W8	TOKUL CREEK	8/13 to	2	A	245	23					0.8 to 2.0	1.3	YES	POSSIBLY	NO
DOWNSTREAM		8/30					16.2-31.7	24.5	14.9-18.9	16.3					
UPSTREAM							16.4-30.8	22.0	14.1-17.5	15.1					
W9	GRIFFIN CREEK	9/11 to	2	A	158	79					-0.3 to 1.1	0.6	UNKNOWN	UNKNOWN	UNKNOWN
DOWNSTREAM		9/29					15.0-33.0	23.5	14.9-16.9	15.8					
UPSTREAM							14.9-30.1	22.6	15.1-17.0	15.9					
E1	INDIAN CREEK	8/19 to	3	A	155	85					0.9 to 2.4	1.9	YES	NO	YES
DOWNSTREAM		9/5					19.1-30.7	24.9	17.8-19.2	18.1					
UPSTREAM							17.7-28.2	23.2	15.7-18.2	16.9					
E2	ROCK CREEK	9/6 to	3	A	760	99					-0.3 to 0.3	-0.1	UNLIKELY	NO	YES
DOWNSTREAM		9/25					17.0-27.0	22.2	10.9-12.8	11.6					
UPSTREAM							17.2-27.8	23.2	11.0-12.9	11.7					
E3	AENEAS CREEK	8/29 to	3	AA	870	84					0.7 to 0.9	0.7	UNKNOWN	UNKNOWN	UNKNOWN
DOWNSTREAM		9/3*					19.4-22.3	20.0	12.1-13.3	12.9					
UPSTREAM		*See Note 3					20.7-24.0	22.4	11.6-12.8	12.4					
E4	SOUTH FORK	8/1 to	1	AA	640	71					0.2 to 0.4	0.3	YES	NO	YES
DOWNSTREAM	DEEP CREEK	8/16					23.7-33.1	29.1	15.7-18.7	17.4					
UPSTREAM							23.6-33.6	30.6	15.1-18.2	17.2					

NOTES:

1) The water temperature differential is based on a comparison of hourly average water temperature values (downstream site minus upstream site).

2) Exceedance of water quality criteria is interpretted as follows:
"YES": clear evidence of exceedance—at least 0.5 degrees C above allowable criteria;
"POSSIBLY": evidence of temperature within 0.5 degrees C of criteria, or within 1.0 degree C and monitored period not representative of critical temperature regime;
"UNLIKELY": monitored period not representative of critical temperature regime, but exceedance would not be expected based on magnitude of increase required to cause exceedance and/or site factors (e.g. elevation, groundwater inflow rate, etc.);
"NO": clear evidence that applicable water quality criteria are met;
"UNKNOWN": data considered inadequate to make a determination—usually because monitored period is not representative of critical temperature regime and monitoring results and/or site factors do not indicate an exceedance is unlikely; in the case of temperature change, because upstream site is not a representative baseline for evaluating temperature change;
"SUSPECTED": exceedance indicated by spot field measurements only—upstream thermograph malfunctioned.

3) Regarding site E3-Aeneas Creek: the downstream thermograph results indicate significant instrument drift occurred after 9/3/90; upstream instrument operated properly through 9/26/90 and recorded maxumum water and air temperatures of 13.9 and 29.9 degrees C, respectively; only data recorded through 9/3/90 is used for comparison.

TABLE 2: DESCRIPTION OF STUDY SITES

RMZ IDENTIFICATION	STREAM NAME	RMZ LENGTH (METERS)	RMZ WIDTH: AVG. & RANGE EACH SIDE (METERS)	% RIPARIAN SHADE: AVG. (RANGE); AT THERMOGRAPH SITES	ELEVATION AT THERMOGRAPH SITES (METERS)	STREAM GRADIENT (%)	DISTANCE FROM DIVIDE (KM)	AVERAGE BANKFULL CHANNEL WIDTH (METERS)	AVERAGE BANKFULL CHANNEL DEPTH (METERS)	WATER DEPTH @ THERMOGRAPH SITES (METERS)	STREAM ORIEN-TATION AZIMUTH (DEGREES)	DISCHARGE (LITERS/ SECOND)
W1	TRIBUTARY	612	15.2	95 (80–99)		8.0		2.4	0.18		343	
DOWNSTREAM	TO TRAP CREEK		(6.1–24.4)	99	73		2.2			0.16		7.9
UPSTREAM				97	122		1.6			0.14		4.8
W2	TRIBUTARY TO	624	9.1	67 (25–99)		0.6		7.0	0.37		187	
DOWNSTREAM	PIONEER CREEK		(3.1–15.2)	68	173		2.4			0.34		4.3
UPSTREAM				87	177		1.8			0.38		2.3
W3	BLACK CREEK	825	14.0	52 (20–99)		1.2		3.7	0.55		244	
DOWNSTREAM			(7.6–24.4)	46	75		2.8			0.19		13.3
UPSTREAM				95	85		2.0			0.18		7.7
W4	NORTH FORK	385	14.0	91 (80–99)		3.1		5.2	0.31		199	
DOWNSTREAM	RABBIT CREEK		(4.0–27.4)	80	179		3.5			0.22		24.1
UPSTREAM				89	191		3.1			0.22		51.8
W5	SOUTH FORK	815	17.4	82 (15–99)		2.5		5.8	0.34		306	
DOWNSTREAM	OHOP CREEK		(4.0–30.1)	85	415		9.5			0.18		89.5
UPSTREAM				93	435		8.7			0.25		60.3
W6	BEAR CREEK	415	9.1	37 (5–60)		8.9		5.2	0.18		342	
DOWNSTREAM			(3.1–30.1)	58	439		4.0			0.16		28.9
UPSTREAM				97	476		3.6			0.13		21.5
W7	NEW POND CREEK	820	14.3	77 (25–99)		4.5		4.9	0.18		259	
DOWNSTREAM			(7.6–30.1)	62	585		5.2			0.20		45.0
UPSTREAM				79	622		4.4			0.24		45.6
W8	TOKUL CREEK	729	10.4	23 (0–99)		0.8		15.8	0.39		189	
DOWNSTREAM			(1.5–21.3)	23	244		7.1			0.29		126.3
UPSTREAM				61	250		6.4			0.34		110.7
W9	GRIFFIN CREEK	575	13.7	79 (20–99)		0.4		11.5	0.21		222	
DOWNSTREAM			(7.6–24.4)	82	157		5.1			0.14		4.3
UPSTREAM				56	159		4.5			0.18		5.1
E1	INDIAN CREEK	785	26.8	95 (85–99)		3.6		3.9	0.18		281	
DOWNSTREAM			(13.7–57.9)	99	134		8.8			0.14		2.3
UPSTREAM				98	162		8.0			0.17		3.5
E2	ROCK CREEK	615	8.8	99 (98–99)		5.9		3.1	0.15		233	
DOWNSTREAM			(7.6–9.1)	98	741		10.1			0.20		17.6
UPSTREAM				96	777		9.5			0.17		NO DATA
E3	AENEAS CREEK	750	22.0	84 (55–99)		3.3		4.3	0.24		45	
DOWNSTREAM			(6.1–50.6)	89	853		15.0			0.21		39.9
UPSTREAM				95	878		14.2			0.20		35.1
E4	SOUTH FORK	475	9.8	71 (50–90)		2.3		7.0	0.37		32	
DOWNSTREAM	DEEP CREEK		(6.1–19.8)	63	634		8.9			0.24		60+ (est.)
UPSTREAM				52	645		8.4			0.27		NO DATA

TABLE 3: ADDITIONAL INFORMATION ON STUDY SITES

RMZ IDENTIFICATION	STREAM NAME	LOCATION (T/R/S)	HARVEST TYPE & SIZE (HECTARES)	APPROX. HARVEST DATE	ONE OR TWO SIDED RMZ	STAND TYPE OTHER SIDE	UPSTREAM STAND TYPE	TREE COUNT (>10 cm DBH per HA) (% Con.146 Hw)	TREE COUNT (all stems per HA,	APPARENT HARVESTING W/I RMZ
W1 DOWNSTREAM UPSTREAM	TRIBUTARY TO TRAP CREEK	T12N/R8W/ S12	CLEARCUT 47.0	3/88 to 7/88	ONE-SIDED	10 YR OLD PLANTATION	STANDING TMBR, 5 YR PLANT.. RECENT CC	280 (3%/97%)	335	NO
W2 DOWNSTREAM UPSTREAM	TRIBUTARY TO PIONEER CREEK	T16N/R6W/ S21	CLEARCUT 47.0	6/88 to 6/89	ONE-SIDED	STANDING TMBR	STANDING TMBR, 25 YR PLANT.	370 (27%/73%)	720	NO
W3 DOWNSTREAM UPSTREAM	BLACK CREEK	T18N/R7W/ S17	CLEARCUT 60.7	3/88 to 1/89	ONE-SIDED	PRE-TFW CC W/ SPARSE SMZ	RECENT CC W/ RMZ	165 (72%/28%)	659	YES
W4 DOWNSTREAM UPSTREAM	NORTH FORK RABBIT CREEK	T21N/R6W/ S28	CLEARCUT 65.6	9/88 to 4/89	TWO-SIDED		STANDING TMBR	389 (13%/87%)	626	NO
W5 DOWNSTREAM UPSTREAM	SOUTH FORK OHOP CREEK	T17N/R5E/ S21	CLEARCUT 45.3	12/88 to 4/89	ONE-SIDED	STANDING TMBR	STANDING TMBR	370 (51%/49%)	507	NO
W6 DOWNSTREAM UPSTREAM	BEAR CREEK	T18N/R5E/ S13&24	CLEARCUT 12.1	7/88 to 7/89	TWO-SIDED		STANDING TMBR	392 (91%/9%)	434	YES
W7 DOWNSTREAM UPSTREAM	NEW POND CREEK	T19N/R7E/ S32&33	CLEARCUT 68.0	9/88 to 7/89	ONE-SIDED	PRE-TFW CC WI SMZ	STANDING TMBR, PRE-TFW CC W/SMZ	637 (52%/48%)	1896	NO
W8 DOWNSTREAM UPSTREAM	TOKUL CREEK	T25N/R8E/ S22	CLEARCUT 46.5	7/88 to 6/89	TWO-SIDED		STANDING TMBR	290 (90%/10%)	413	NO
W9 DOWNSTREAM UPSTREAM	GRIFFIN CREEK	T25N/R8E/ S18	CLEARCUT 2.4	9/88 to 8/89	ONE-SIDED	STANDING TMBR	STANDING TMBR	480 (20%/80%)	715	NO
E1 DOWNSTREAM UPSTREAM	INDIAN CREEK	T4N/R11E/ S30	CLEARCUT & PARTIAL CUT 32.4	9/89 to 6/90	TWO-SIDED		STANDING TMBR	342 (22%/78%)	669	NO
E2 DOWNSTREAM UPSTREAM	ROCK CREEK	T16N/R15E/ S9	PARTIAL CUT 49.4	5/88 to 5/89	ONE-SIDED	RANGELAND W/ SPARSE TMBR	BARE SCREE SLOPE, RANGELAND W/ SPARSE TMBR	473 (16%/84%)	1161	NO
E3 DOWNSTREAM UPSTREAM	AENEAS CREEK	T36N/R30E/ S32	PARTIAL CUT 194.3	12/89 to 6/90	TWO-SIDED		STANDING TMBR	585 (78%/22%)	1263	NO
E4 DOWNSTREAM UPSTREAM	SOUTH FORK DEEP CREEK	T38N/R41E/ S29	PARTIAL CUT 4.1	8/89 to 6/90	ONE-SIDED	STANDING TMBR & RANGELAND WI SPARSE TMBR	STANDING TMBR	700 (12%/88%)	2618	NO

W1: Tributary to Trap Creek

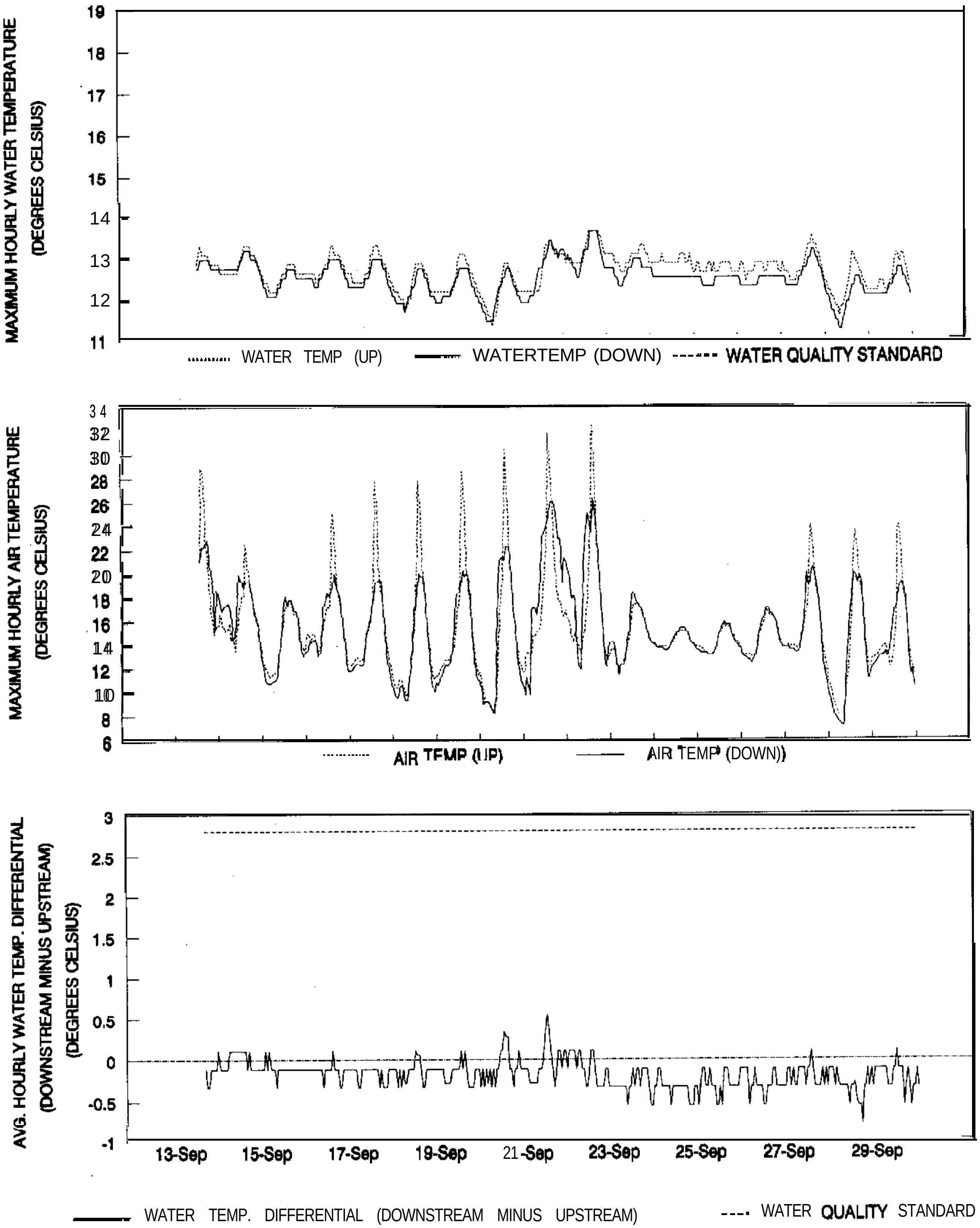
	Elevation	RMZ Shade	RMZ Width
BMP CONSIDERED EFFECTIVE	100 meters	Ave: 95% Range: 80-99%	Ave: 15.2 meters Range: 6.1-24.4 meters

This RMZ is located in central Pacific County along a type 2, Class A stream. Across from the one-sided RMZ is a ten year old Douglas fir plantation, with no RMZ, but with a thin strip of alder overstory along the stream. Upstream of the 612 meter RMZ, mature second-growth timber provides relatively dense riparian canopy cover for approximately 300 meters on the east side of the stream. Across from the second-growth, a young plantation covers the uplands west of the stream. Upstream of this, the stream branches into several headwater tributaries traversing recent clearcut, with no RMZs.

Tributary to Trap Creek was one of the last sites monitored, with thermographs deployed from September 13 to September 29, 1990. Neither the upstream or the downstream site exceeded the water quality standard maximum of 18.3°C. In fact, maximum daily temperatures did not exceed 14.0°C during the monitoring period. The maximum daily water temperature differential (downstream minus upstream) ranged from -0.1 to 0.6°C, and much of the time the differential was less than zero (i.e. the upstream site was warmer). Comparisons between maximum daily air temperatures for the monitored period and the July 15-August 15 period at the nearby Raymond weather station (located about 17 kilometers northwest) indicate that the monitored period does not represent critical temperature conditions. The highest 2-day average for the monitored period was about 4°C lower than that for the July 15-August 15 period.

It is unlikely that the maximum allowable criterion of 18.3°C would be exceeded even under critical summer temperature conditions, as this would require an increase of about 5°C from the maximum observed temperature. With an average shade level of 95%, such an increase seems unlikely. Also, with this relatively wide, highly shaded RMZ, the harvest probably did not remove any appreciable amount of shade from the stream. We consider the BMP effective in this case. Based on the maximum water temperature differentials observed, we conclude that this RMZ is also effective at meeting applicable water quality standards pertaining to incremental change. The primary factors contributing to BMP effectiveness are the high level of shade within the RMZ and a relatively high rate of groundwater inflow. The estimated streamflow at the downstream thermograph site was about 1.6 times that at the upstream site, and there were no surface tributaries between the sites.

W1: TRIBUTARY TO TRAP CREEK



PERIOD MONITORED **(13-SEPT** TO **29-SEPT** 1990)

W2: Tributary to Pioneer Creek

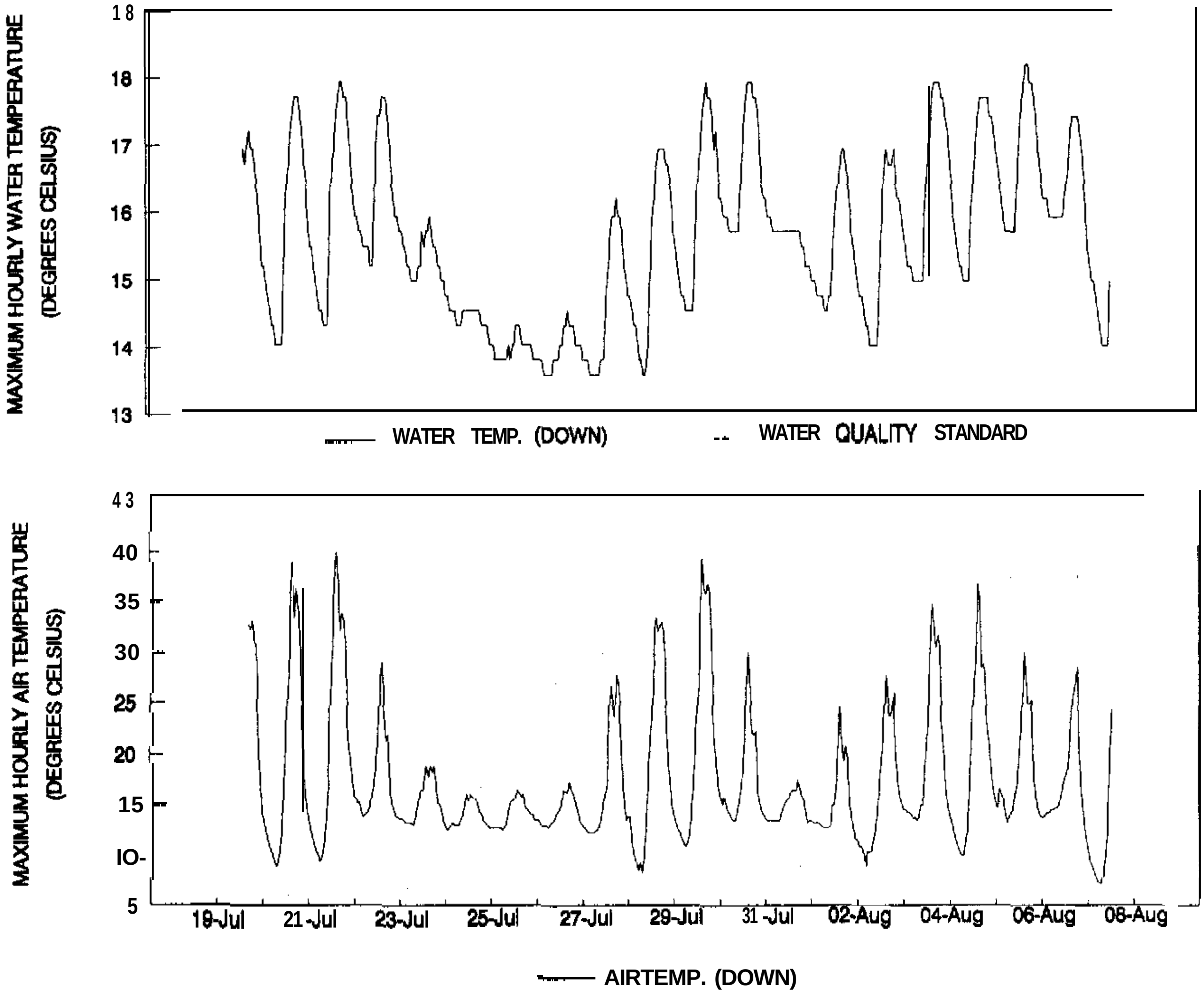
	Elevation	RMZ Shade	RMZ Width
BMP CONSIDERED INEFFECTIVE	175 meters	Ave: 67% Range: 25-99%	Ave: 9.1 meters Range: 3.1-15.2 meters

This one-sided RMZ is located in southern Grays Harbor County on the west side of a type 3, Class A stream. Land on the east side of the stream is in mature second growth timber. Upstream of the RMZ, there is mature second growth *timber* in the riparian zone and on the uplands east of the stream; on the uplands west of the stream there is a 20 year plantation for a stream distance of about 350 meters, with mature second growth upstream of that. In some spots the RMZ was less than the minimum required width of 7.6 meters and contained a relatively sparse number of leave trees. Judging from the Department of Wildlife database and field observations, there may have been a minor amount of harvesting within the RMZ. Within the study area, this tributary to Pioneer Creek is a relatively wide, low gradient stream traversing a wetland, with several beaver dams and a series of moderately deep pools.

Tributary to Pioneer Creek was monitored from July 19 to August 7. Due to equipment malfunctions, the upstream thermograph did not produce useable data, so no comparisons of hourly temperature differentials can be made. However, based on field checks using mercury thermometers, the upstream site was 4 to 6°C cooler at the time of thermograph deployment and retrieval. Consequently, it is suspected that water quality criteria applying to incremental increases in temperature were exceeded at this RMZ. Maximum daily water temperature at the downstream site ranged from 14.3 to 18.2°C, and temperatures approached or exceeded 18°C on five of nineteen days. Since thermographs are considered accurate to ± 0.5°C, these findings represent possible exceedances of the 18.3°C water quality criterion.

This RMZ prescription is, considered ineffective at preventing adverse stream temperature increases. Although the wide stream channel may limit the effectiveness of streamside shading in some spots along this RMZ, we believe that leaving more shade trees and/or a wider RMZ on the west side of this stream may have provided additional afternoon shade sufficient to meet water quality criteria. The unharvested reach upstream of this RMZ is also characterized by considerable beaver activity with wide pools, and yet it is a good deal cooler based on our field checks. We noted considerably more woody vegetation in the upstream reach than in the RMZ, which could more effectively shade the stream. The combination of relatively low elevation and the low gradient/beaver influenced stream morphology result in a situation that may be highly sensitive to removal of even minor amounts of riparian shade (e.g. large trees and/or nonmerchantable woody vegetation).

W2: TRIBUTARY TO PIONEER CREEK



PERIOD MONITORED (19-JULY TO 7-AUG 1990)

W3: Black Creek

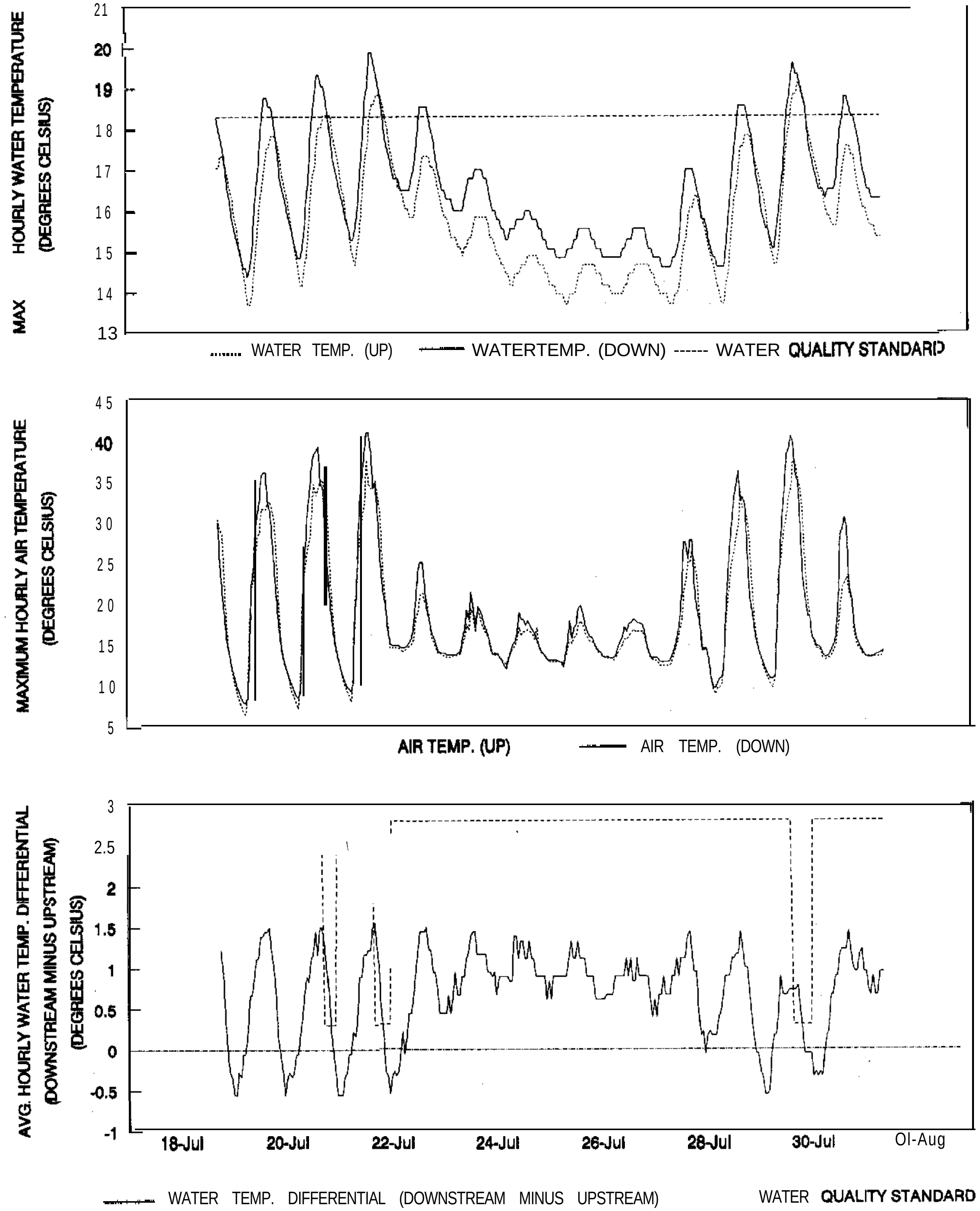
	Elevation	RMZ Shade	RMZ Width
BMP CONSIDERED INEFFECTIVE	80 meters	Ave: 52% Range: 20-99%	Ave: 14.0 meters Range: 7.6-24.4 meters

This one-sided RMZ is located in central Grays Harbor County, along the south side of a type 3, Class A stream. Land on the north side of the stream is clearcut with reproduction less than five years old and a narrow zone of riparian overstory vegetation left under pre-TFW regulations. Upstream of the RMZ are more recent clearcuts with, slightly wider and apparently more dense riparian zones. Although the Department of Wildlife sampling data does not show a large amount of harvesting within the leave tree perimeter, we observed several recent stumps during field visits. This RMZ had the lowest density of standing trees of all the study sites. Some portions of the RMZ were completely devoid of shade trees

Temperature conditions in this RMZ were monitored from July 18 to July 31. The water quality criterion for maximum temperature was exceeded on seven of twelve days at the downstream site and three days at the upstream site. We are not able to determine whether the criteria for incremental increase are exceeded. Data from the upstream monitoring site cannot serve as a baseline for evaluating the temperature change associated with harvesting the study unit in this case. This is because the riparian conditions of the upstream reach are not considered representative of pm-harvest conditions for the downstream reach. If the upstream site were considered representative of baseline conditions, the criteria for incremental increase would have been exceeded on three of 12 days, **as shown on the plot on** the facing page. Since there was standing timber on the south side of the stream, we believe pre-harvest conditions may have been somewhat cooler than the observed background. Although background conditions in this case represent significant disturbance by **clearcutting,** the upstream site was within water quality standards 50% more often than the downstream site. The observed increase occurred despite the influence of groundwater inflow in the monitored reach, as indicated by a 72% increase in discharge between the upstream and downstream sites.

This RMZ is not effective at maintaining stream temperature within water quality standards. BMP ineffectiveness is primarily attributed to the combination of low elevation and low stream shading. A severely disturbed riparian zone across from the study RMZ is a significant factor in the overall midstream shade level. However, leaving additional shade within the study RMZ on the south side of the stream (e.g. a wider RMZ with no removal of shade trees) may have provided sufficient temperature protection. If the stream was already exceeding criteria before harvest, then the only way for the BMP to be effective **would have** been to ensure that no stream shading was removed by the harvest.

W3: BLACK CREEK



PERIOD MONITORED (W-JULY TO 31-JULY 1990)

W4: North Fork Rabbit Creek

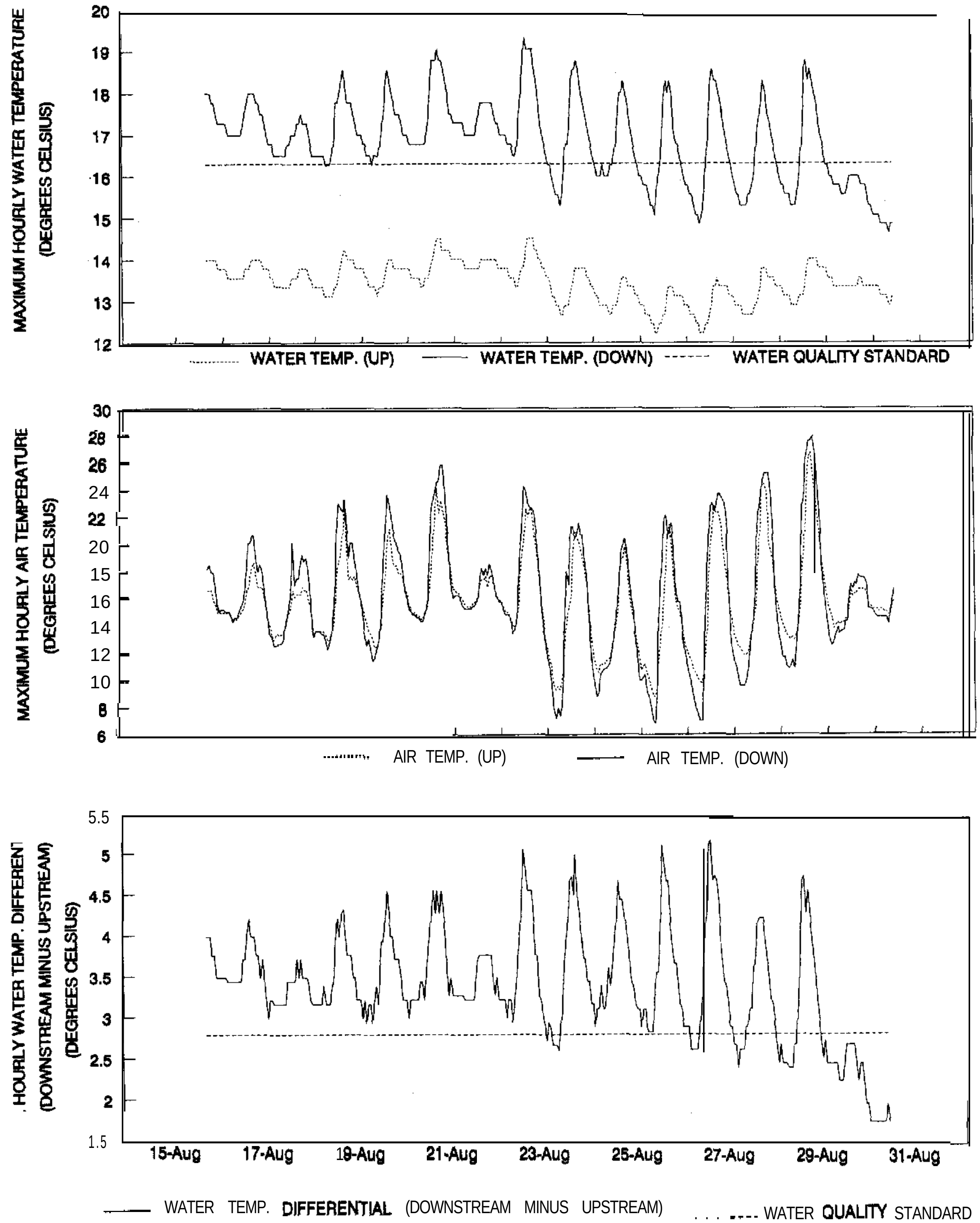
BMP	Elevation	RMZ Shade	RMZ Width
CONSIDERED INEFFECTIVE	185 meters	Ave: 91% Range: 80-99%	Ave: 14.0 meters Range: 4.0-27.4 meters

The two-sided RMZ along North Fork Rabbit Creek is located in western Mason County. North Fork Rabbit Creek is a type 3, Class AA stream. The area upstream of the RMZ is in mature second growth timber on both sides of the stream for at least 600 meters. The stream is aggraded within the lower portion of the RMZ. Riparian shade was observed to be sparse in a couple of locations, although this is not reflected in the Department of Wildlife measurements. RMZ length is given in Table 2 as 385 meters, but the downstream thermograph was originally installed at 440 meters. After the initial installation of the thermistor in flowing water about 0.1 meter deep, the downstream site went dry. It was relocated to a site with steady 'flow as soon as the problem became evident. The initial deployment was on August 6, with the downstream thermograph relocated on August 15. Data recorded before the relocation is not used for evaluation of BMP effectiveness.

Weather between August 15 and 31 is not considered representative of critical temperature conditions. Maximum air temperatures recorded at the RMZ between August 6 and 14 were about 12°C higher than the period afterwards, and these higher air temperatures were associated with increased water temperatures at both thermograph sites. Despite having less than critical conditions, the water quality criterion for maximum temperature was exceeded at the downstream monitoring site on 14 of 15 days. Maximum water temperature exceeded 19°C at the downstream site. The water temperature differential between the upstream and downstream sites exceeded 3°C on most days, ranging as high as 5.2°C. Streamflow estimates indicate that North Fork Rabbit Creek is a losing stream in this reach; discharge estimated at the downstream site was about half of that at the upstream site. It is likely that loss of streamflow, or more importantly, the lack of groundwater inflow within the study reach, has a significant influence on stream temperature in the lower portion of the RMZ.

The BMP is considered ineffective in this case. We believe that a wider RMZ and/or retaining all shade trees within the RMZ would have provided additional temperature protection. We do not know what pre-harvest water temperatures were in the lower reaches of this RMZ, but it is likely that they were elevated relative to the upstream site because of the flow loss. In such a situation, the only way to ensure BMP effectiveness would have been to design the RMZ so that the pre-harvest level of shade was maintained. Due to the obvious flow loss in the lower portion of the RMZ, the upstream data is not representative of pre-harvest conditions within the RMZ reach. Therefore, we cannot determine whether the criteria for temperature change have been exceeded as a result of the harvest.

W4: NORTH FORK RABBI CREEK



PERIOD MONITORED (**15-AUG** TO **30-AUG** 1990)

W5: South Fork Ohop Creek

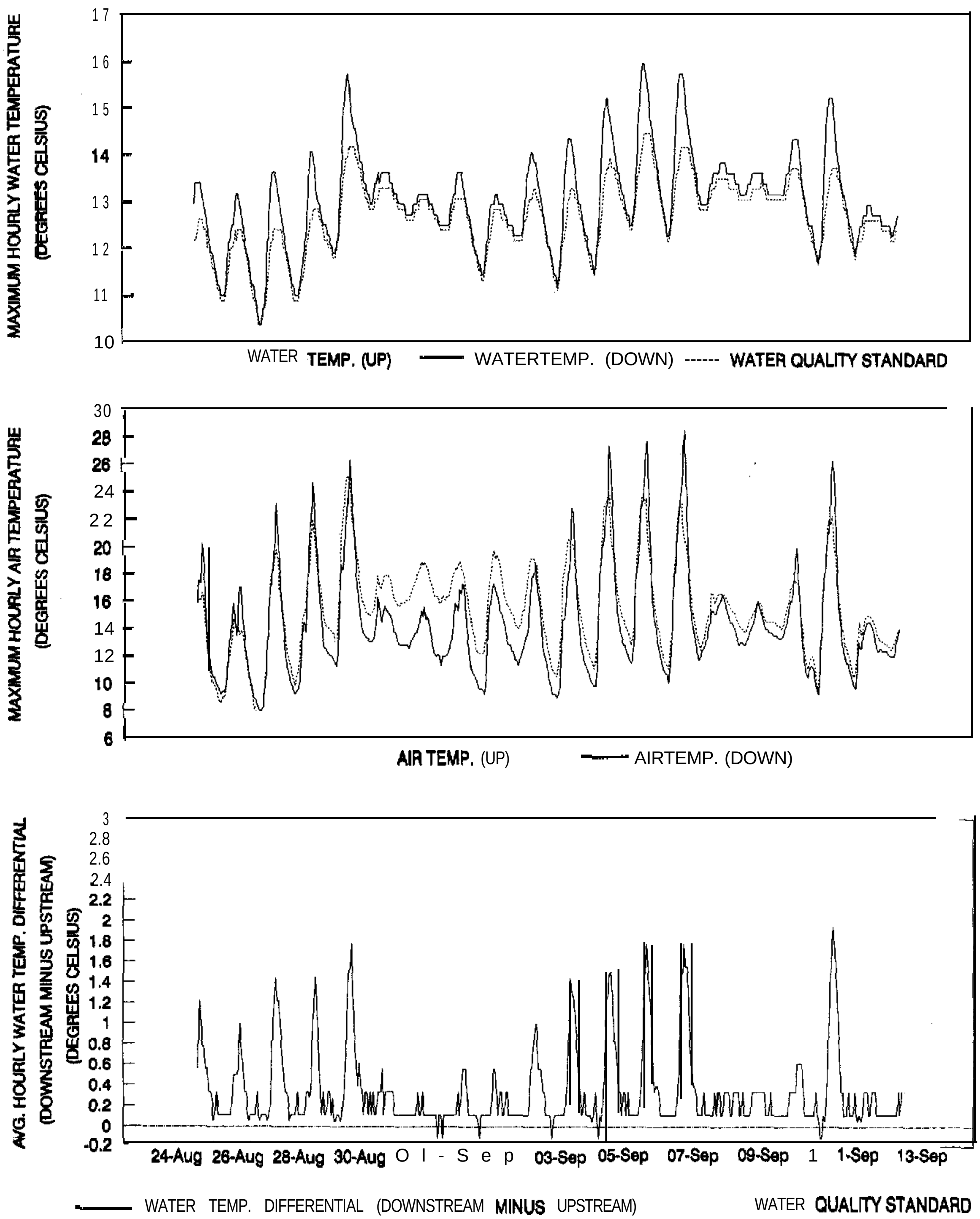
	Elevation	RMZ Shade	RMZ Width
BMP CONSIDERED INEFFECTIVE	425 meters	Ave: 82% Range: 15-99%	Ave: 17.4 meters Range: 4.0-30.1 meters

This one-sided RMZ is located in central Pierce County along South Fork Ohop Creek, which is a Class AA, type 3 stream. The land across from and upstream of the harvest unit is covered in mature standing timber.

This creek was monitored from August 24 to September 12. This period is not considered representative of critical temperature conditions. The highest two-day average air temperature for this period was 8°C lower than the maximum recorded at the Mud Mountain Dam weather station, about 19 kilometers to the northeast. In terms of the effectiveness of the RMZ at achieving water quality criteria, it is possible that the criterion for maximum temperature may be exceeded for this Class AA stream. Maximum observed temperature was within 0.4°C of the criterion on one day and within 0.6°C on two additional days. Considering instrument accuracy, this indicates possible exceedance of the maximum temperature criterion. It is also considered possible that the criteria for incremental increase in temperature would be exceeded at this site under critical temperature conditions. The observed average hourly temperature increase between upstream and downstream monitoring sites was within 1.0°C of the 2.8°C criterion on four of 19 days.

For the purposes of our evaluation, this RMZ is considered ineffective at meeting water quality standards. The primary site factor contributing to BMP ineffectiveness is tbe level of mid-channel shade that remained following harvest. Although the average shade level is a moderately high 82%, some portions of the RMZ had very low shade. The water quality standards classification is an administrative factor that influenced the determination of BMP effectiveness in this case. If this were a Class A stream, no exceedances of the maximum temperature criteria would be indicated, and the BMP might be considered effective.

W5: SOUTH FORK OHOP CREEK



PERIOD MONITORED (24-AUG TO 12-SEPT 1990)

W6: Bear Creek

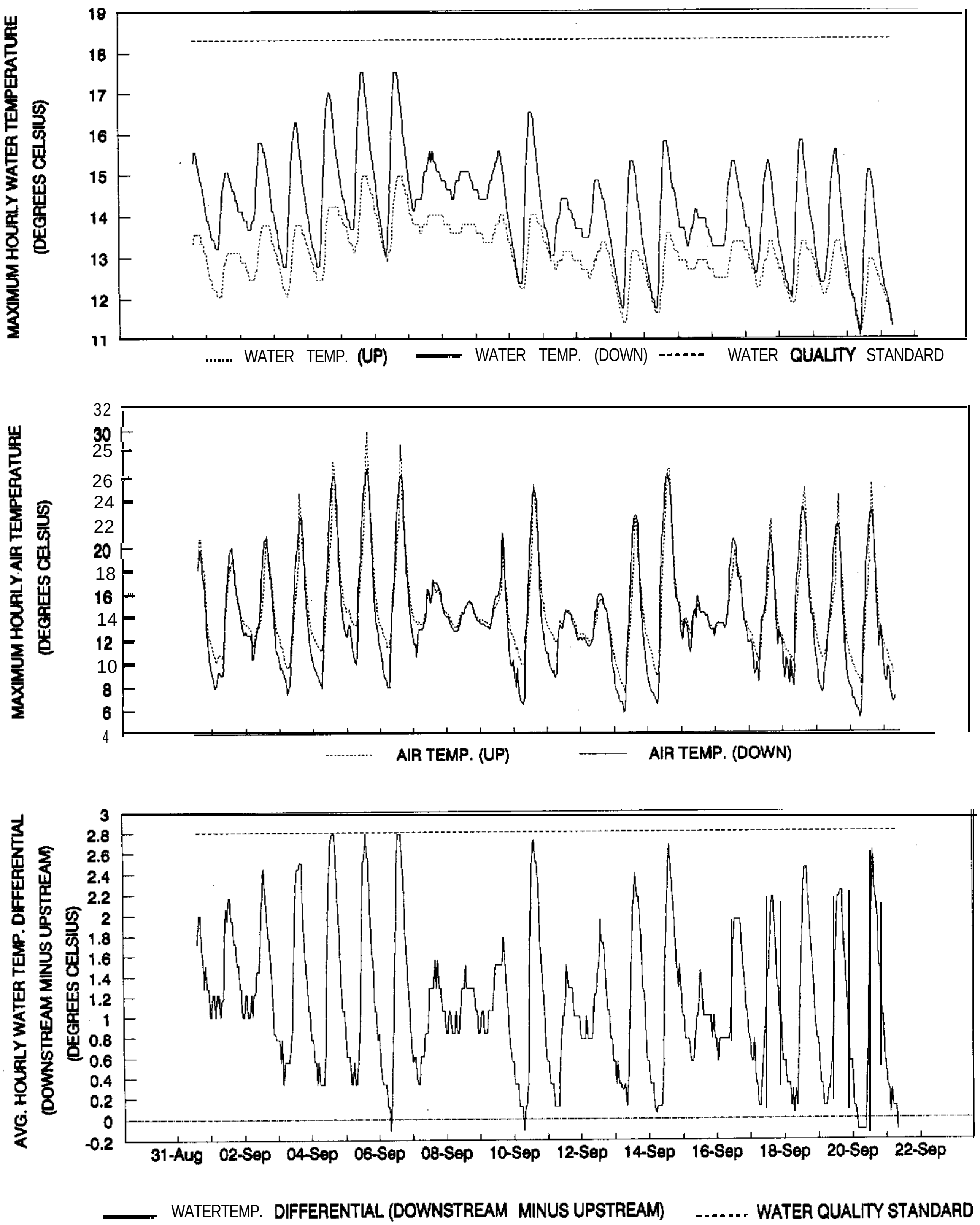
BMP CONSIDERED INEFFECTIVE	Elevation	RMZ Shade	RMZ Width
	465 meters	Ave: 37% Range: 5-60%	Ave: 9.1 meters Range: 3.1-30.1 meters

The two-sided RMZ along Bear Creek (Class A) is located in north-central Pierce County. The 30-acre harvest unit was a salvage cut of a second growth timber stand that had blown down during a winter storm. Both standing and downed trees were harvested. Upstream of the harvest unit for at least 600 meters the land on both sides of the stream is covered in mature standing timber. The Department of Wildlife survey noted a significant amount of harvesting within the RMZ. Under an alternative plan approved for this harvest, all dominant and some codominant timber was removed from the east (leeward) side of the stream, while all nonmerchantable, deciduous, and most codominant timber was left within a 25 ft. RMZ on the west side. The reasoning for the alternative plan was the high probability that timber left in the RMZ would blow down, and that timber on the east side of the stream would not contribute large organic debris (LOD) if downed because of the wind direction.

The temperature conditions in Bear Creek were monitored from August 31 to September 21. This period was not representative of critical temperature conditions. The highest two-day average air temperature during this period was 8°C cooler than the highest mid-summer two, day average at the Mud Mountain Dam weather station, about 5 kilometers north of the site. The maximum temperature at the downstream thermograph was within 0.8°C of the 18.3°C criterion on two consecutive days which correspond to the period of highest recorded air temperature. In the absence of critical temperature conditions, and in consideration of instrument accuracy, this indicates a possible exceedance of the maximum temperature criterion. During this same period, the maximum daily water temperature differential reached 2.8°C on three consecutive days. However, for this RMZ the data from the upstream monitoring site are not considered representative of pre-harvest conditions for the study unit because of the blowdown situation that existed prior to harvest/salvage. Therefore, we cannot determine whether the criteria for temperature change are exceeded.

This RMZ is not considered effective at achieving water quality standards. The primary factor contributing to BMP ineffectiveness is the low level of riparian canopy closure. The blowdown resulted in considerable amounts of LOD within the RMZ, which has the potential to shade the stream, but this type of shade is not reflected in the densiometer measurements. Harvest of standing trees within the RMZ, including intense harvesting on one side, has probably limited the effectiveness of the BMP. Even though overstory shading was reduced as a result of blowdown, the remaining dominant and other trees could have provided more shading, either as standing trees or possibly LOD in the event of future windthrow.

W6: BEAR CREEK



PERIOD MONITORED (31-AUG TO 21-SEPT 1990)

W7: New Pond Creek

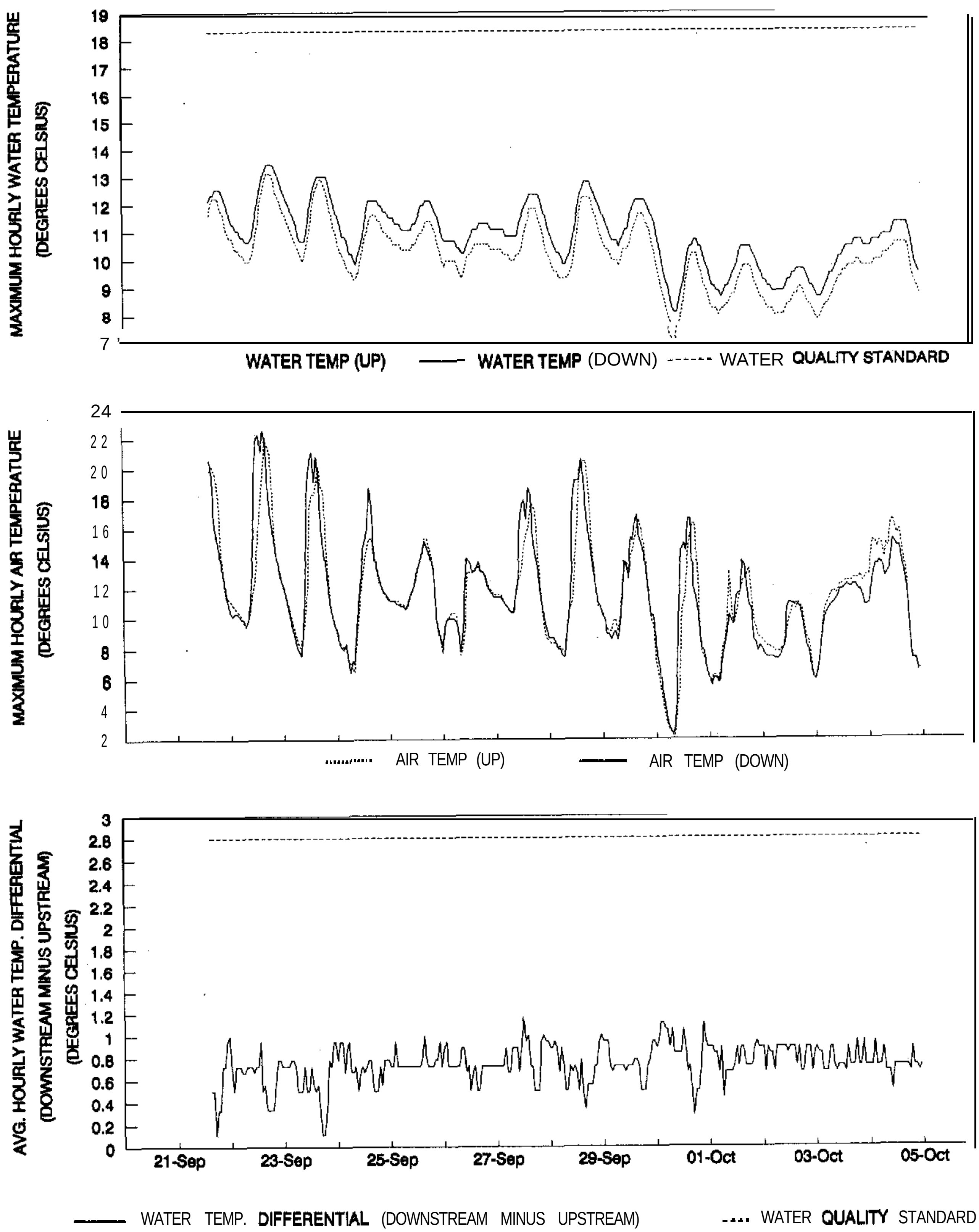
	Elevation	RMZ Shade	RMZ Width
BMP			
CONSIDERED	**610 meters**	**Ave: 77%**	**Ave: 14.3 meters**
EFFECTIVE		**Range: 25-99%**	**Range: 7.6-30.1 meters**

This one-sided RMZ on New Pond Creek (Class A) is located in north central Pierce County. The area opposite the study RMZ and upstream to the headwaters appears to have been clearcut harvested prior to the TFW RMZ regulations. However, the watershed on the same side and upstream of the study RMZ is mature second-growth for a distance of about 400 meters.

This site was monitored from September 21 to October 4. The highest two-day average air temperature recorded during this period at the Mud Mountain Dam weather station (5 kilometers north of the study site) was 4°C below the maximum summertime two-day average. The solar angle during this period is also considerably lower than during mid-summer. Consequently, the data is not considered representative of critical conditions. The maximum daily water temperature recorded at the downstream monitoring site ranged from 9.6 to 13.4°C. The maximum daily water temperature differential ranged from 0.9 to 1.2°C, with a medii value of 0.9°C.

The BMP is considered effective in this case. The creek did not exceed the maximum water quality criterion of 18.3°C, and it is considered unlikely that it would exceed this temperature under critical conditions, given the relatively high elevation of this reach and the large temperature increase that would have to occur to exceed the criterion. Although an increase in water temperature through the RMZ was observed, it is considered unlikely that the criterion for maximum allowable temperature change would be exceeded during critical temperature regimes at this site because of its relatively high elevation.

W7: NEW POND CREEK



PERIOD MONITORED (21 -SEPT TO 4-OCT 1990)

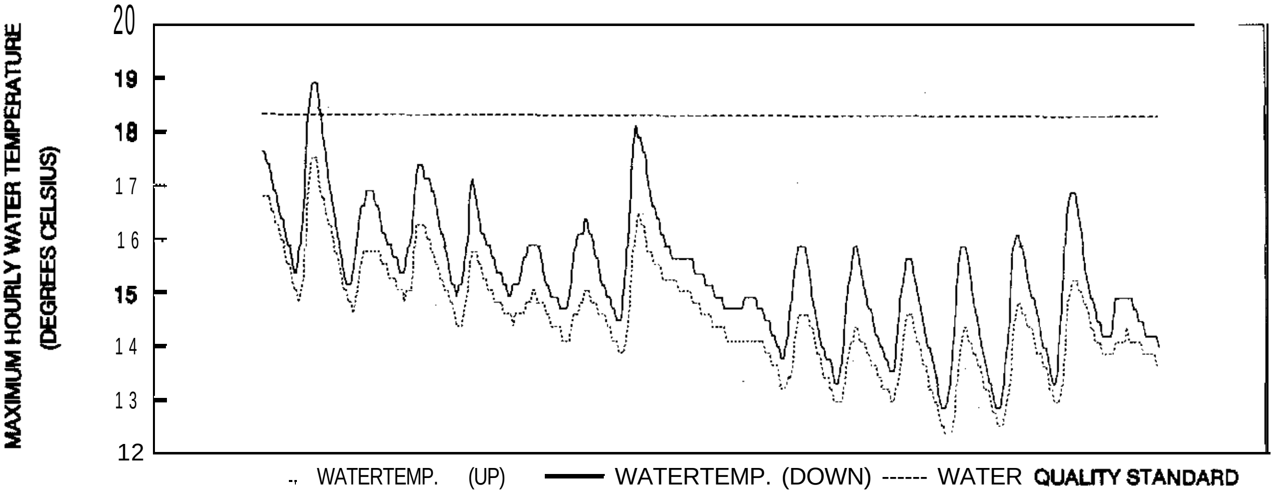
W8: Tokul Creek

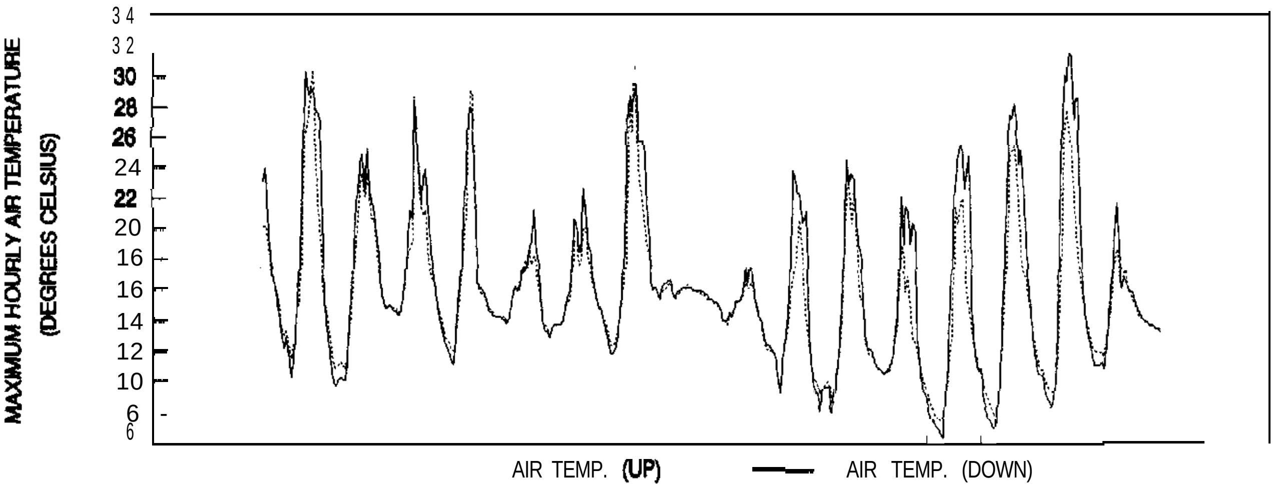
	Elevation	RMZ Shade	RMZ Width
BMP CONSIDERED INEFFECTIVE	245 meters	Ave: 23% Range: 0-99%	Ave: 10.4 meters Range: 1.5-21.3 meters

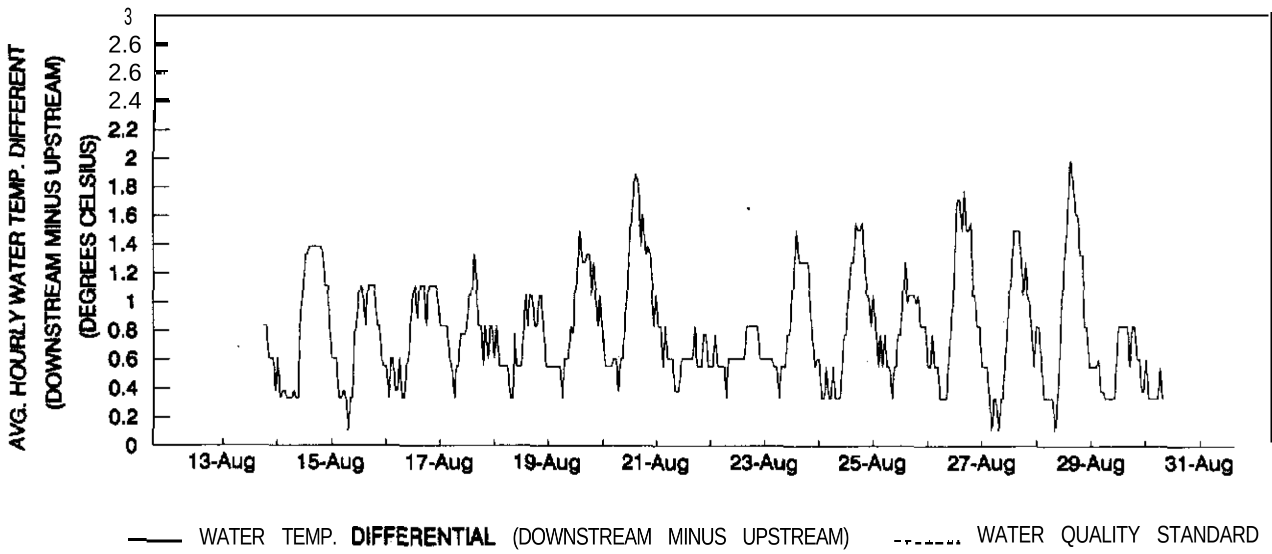
This two-sided RMZ along Tokul Creek is located in north-central Ring County. Tokul Creek is a type 2, Class A stream. Upstream from the RMZ the land is in mature standing timber for several hundred meters. The stream reach above and through the study RMZ has considerable beaver activity, resulting in large pools alternating with braided stream segments. There is a good deal of open water in some segments impounded by beaver dams. Shade levels within the RMZ varied widely, with some portions completely devoid of shade trees. In the undisturbed reach above the RMZ, we observed more nonmerchantable woody vegetation than was present in portions of the RMZ. It appears that some areas of nonmerchantable vegetation were cleared within the RMZ to accommodate hi-lead cable logging systems. Tokul Creek has the highest discharge of all streams in this study, and discharge estimates indicate a slight increase in flow between the upstream and downstream monitoring sites.

The study reach was monitored from August 13 to August 30. This period is not considered representative of critical conditions. The highest two-day average air temperature during the monitoring period was 8.5°C below the highest two-day average for the summer, based on records from the Snoqualmie Falls weather station 12 kilometers south of the study site. We recorded a maximum water temperature of 18.9°C on one day at the downstream monitoring site, which exceeded the water temperature criterion. A maximum temperature of 18.1°C was recorded on another day. Maximum water temperature recorded at the upstream monitoring site was 175°C. Based on these results, the BMP is not considered effective at meeting water quality standards for maximum temperature. In the case of this low gradient, moderately low elevation stream, it may be that the only way for the RMZ to have been effective would have been to design it such that no stream shading was removed, retaining any large trees and all nonmerchantable woody vegetation that provided shade. We believe the criteria for maximum water temperature change may be exceeded at this RMZ as well. The upstream site was within 0.5 of 18.0°C once during the monitoring period. When the upstream site, which is essentially under natural conditions, reaches this level the criterion for allowable change becomes 0.3°C. This temperature change was consistently exceeded during the monitoring period, even though it was not representative of critical temperature conditions.

W8: TOKUL CREEK







PERIOD MONITORED (13-AUG TO 30-AUG 1990)

W9: Griffin Creek

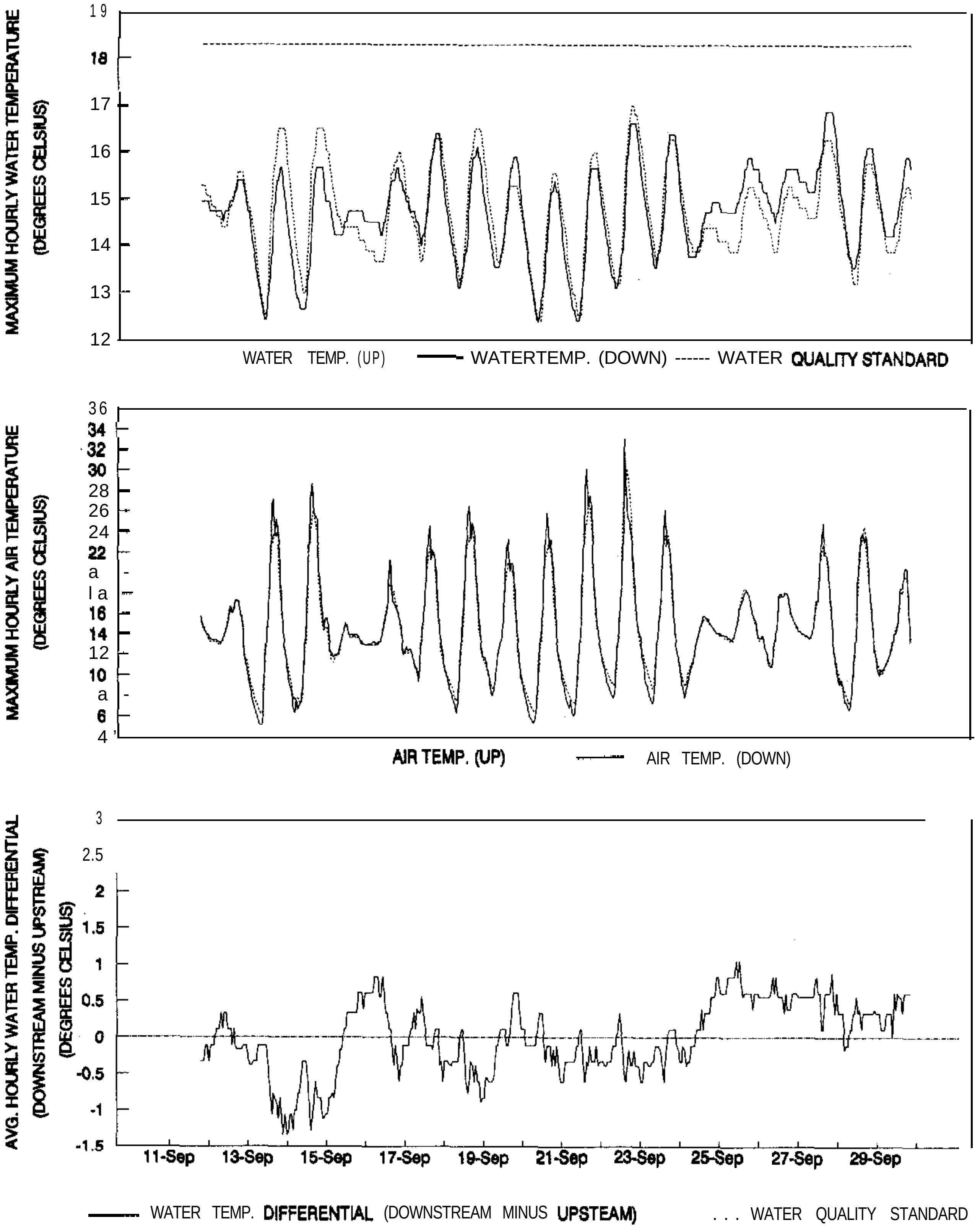
	Elevation	RMZ Shade	RMZ Width
BMP EFFECTIVENESS NOT DETERMINED	158 meters	Ave: 79% Range: 20-99%	Ave: 13.7 meters Range: 7.6-24.4 meters

Griffin Creek is a type 2, Class A stream with a one-sided RMZ. Land on the opposite side of the RMZ is in standing timber, as is the area upstream for at least 600 meters. The area upstream of the RMZ also has beaver ponds and associated wetlands, with some open water segments. The beaver activity extends through the upper portion of the RMZ, but the stream is free-flowing in the lower portion.

Griffin Creek was monitored from September 11 to September 29. The maximum two-day average air temperature at the nearby Snoqualmie Falls weather station during the monitoring period was 4.5°C below the maximum two-day average for the summer. Perhaps more important, the midday solar angle is approximately 15-20 degrees lower during late September than it is in mid-summer. Therefore, the results are not considered representative of critical temperature conditions. We did not observe any exceedances of water quality criteria during the monitoring period. Due to the lateness of monitoring at this site, however, we cannot determine whether the RMZ is effective at maintaining water temperature within the maximum criterion of 18.3 degrees.

Likewise, while we observed that the upstream site often had higher water temperatures than our downstream monitoring site, we are unable to determine whether the criteria for temperature change are met. This is because the upstream site is not suitable as a baseline for evaluating temperature change associated with the harvest in this case. Griffin Creek has considerable beaver activity which has resulted in large, deep pools alternating with braided stream segments upstream of and in the upper portion of the study RMZ. However the stream and riparian zone are considerably different in the lower 200 meters of the RMZ. The stream is free-flowing and the canopy generally closes over the stream in this lower portion. Because of these differences, the upstream site is not representative of pre-harvest conditions at the downstream site, and the temperature differential observed does not reflect the temperature change associated with the timber harvest.

W9: GRIFFIN CREEK



PERIOD MONITORED (1 1-SEPT TO 29-SEPT 1990)

E1: Indian Creek

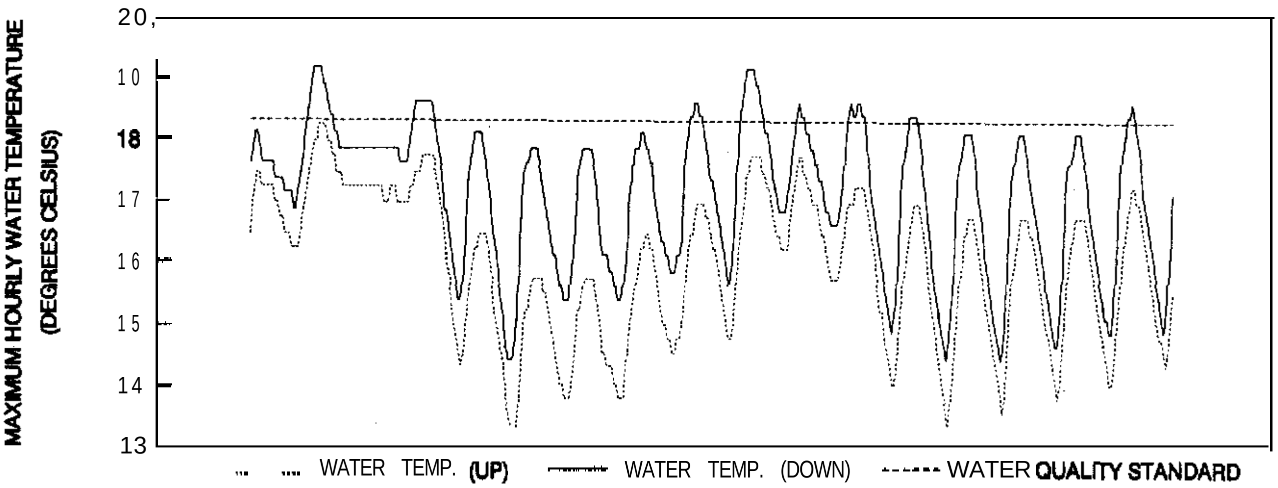
	Elevation	RMZ Shade	RMZ Width
BMP CONSIDERED EFFECTIVE	155 meters	Ave: 95% Range: 85-99%	Ave: 26.8 meters Range: 13.7-57.9 meters

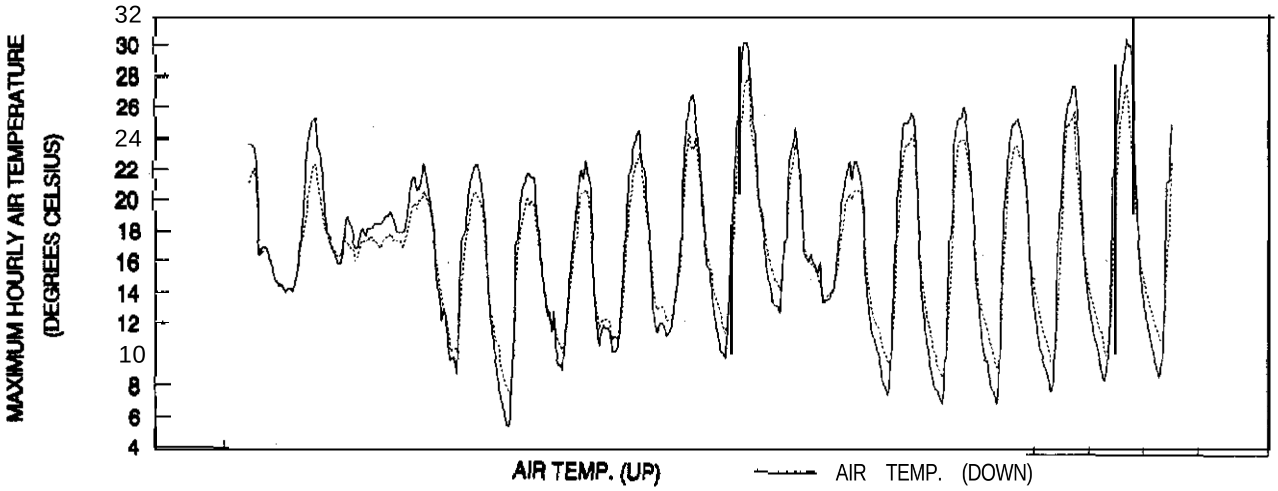
This two-sided RMZ is located in southwest Klickitat County, approximately 2 kilometers northeast of the town of Husum. In addition to a high riparian shade level, the stream is topographically shaded by a high south bank in the upper portion of the RMZ. The harvest unit was partial cut to the north of the creek, and clearcut to the south. The area above the monitoring site is in standing timber with scattered residential dwellings. Discharge estimates indicate a slight loss of flow between the upstream and downstream monitoring sites. During field surveys, we discovered a 15 centimeter diversion pipe about 240 meters upstream of the downstream thermograph site. Because of this surface flow diversion, it is unclear whether this is a gaining or loosing reach with respect to groundwater.

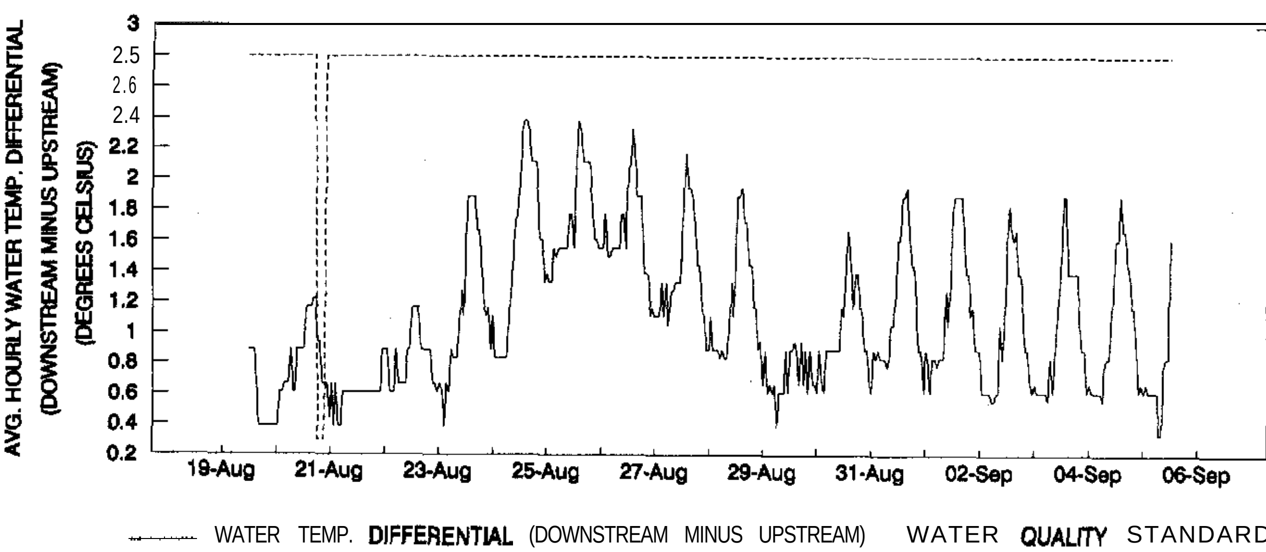
Indian Creek was monitored from August 19 to September 5. During this period the maximum water temperature criterion of 18.3°C was exceeded eight times at the downstream thermograph site. These exceedances occurred during a period which may not be representative of the critical temperature regime for this stream. Examination of weather information from the Mount Adams Ranger Station's weather station, located approximately 20 kilometers north-northeast of the study site, indicates that the maximum two-day average air temperature occurring during the monitoring period was 55°C lower than the highest mid-summer two-day average.

We believe that the exceedances noted do not reflect ineffectiveness of the BMP. Shade levels are consistently high withii this RMZ, and the average width of the RMZ is over 26 meters. In fact, this was the widest RMZ in the study. It is unlikely that any substantial amount of additional shade could have been left in this case in order to achieve water quality standards. In terms of the criteria for temperature change, although the downstream site was warmer than the upstream site, there is no evidence that this increase was caused by the timber harvest. The water withdrawal may have an influence on the temperature sensitivity of this stream reach.

El: INDIAN CREEK







PERIOD MONITORED (19-AUG TO 5-SEPT 1990)

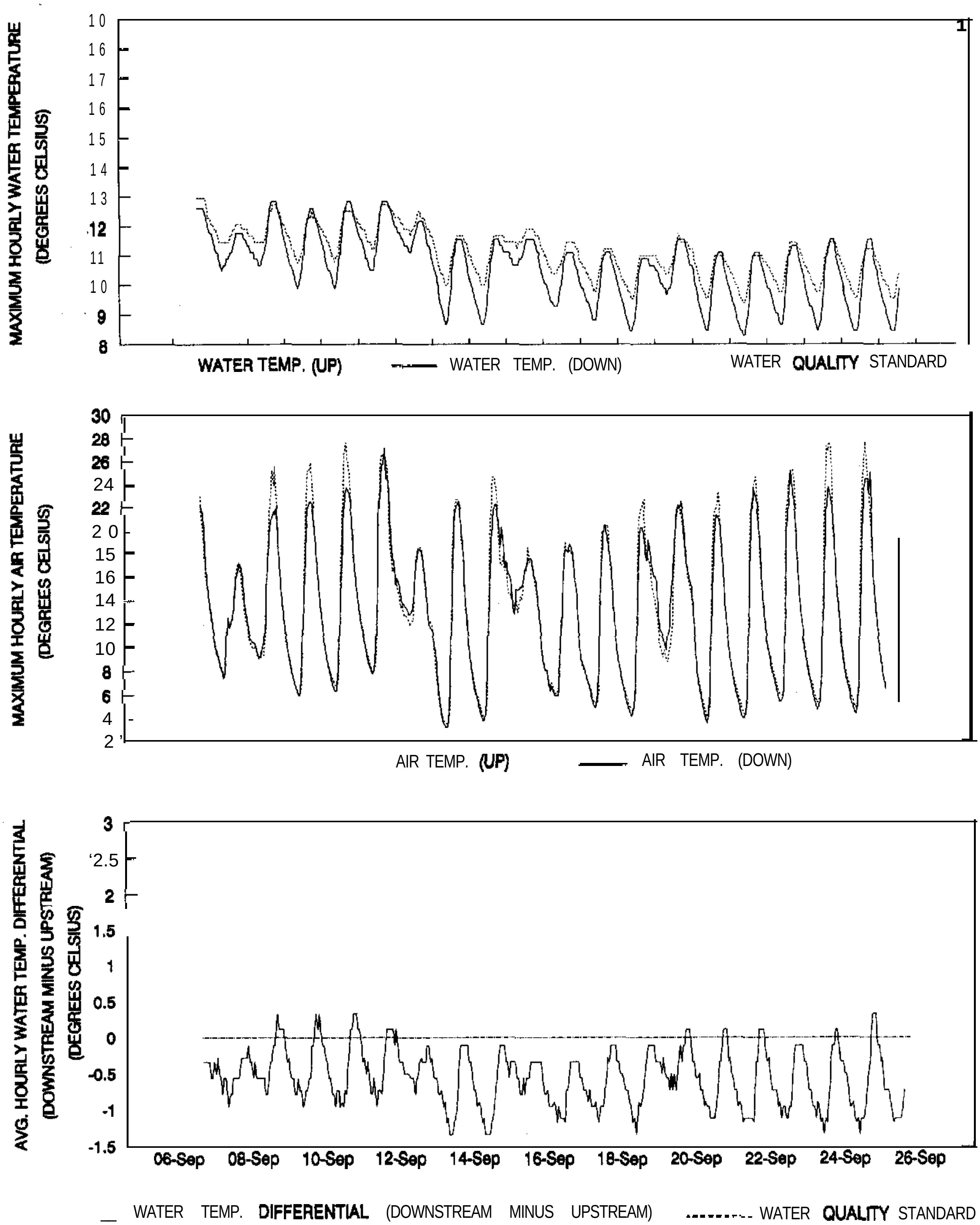
E2: Rock Creek

	Elevation	RMZ Shade	RMZ Width
BMP			
CONSIDERED	760 meters	Ave: 99%	Ave: 8.8 meters
EFFECTIVE		Range: 98-99%	Range: 7.6-9.1 meters

This RMZ is located in northern Yakima County approximately 300 meters downstream from the Mount Baker-Snoqualmie National Forest boundary. Rock Creek is a type 3, Class A stream. The RMZ is one-sided (southeast side), and the harvest was a partial cut. The opposite side was partial cut many years ago and is mostly open range land with sporadic large pines. The area upstream of the RMZ is composed of bare rock (scree) slopes, rangeland, and sparse timber. Portions of the RMZ are characterized by a dense growth of willows and other woody vegetation, resulting in a relatively high stem count (1161 stems/hectare) .

Rock Creek was monitored from September 6 to September 25. Water quality standards were not exceeded during the monitoring period. The upstream site usually had higher water temperatures than the downstream site, indicating that this RMZ (and/or another factor such as groundwater inflow) has a cooling effect on Rock Creek. However, air temperatures indicate that the critical temperature regime was not tested during this monitoring period. The highest two-day average air temperature for the monitored period was about 5°C below the summer maximum, based on Cle Elum weather station records. However, it is unlikely that this high elevation site with almost complete canopy closure would exceed the Class A criterion of 18.3°C even under critical conditions. In order to exceed the criterion, maximum water temperatures would have to increase by over 5°C over our observed temperatures. Even if the criterion were exceeded, the high average shade level (99%) indicates that the harvest had little if any impact on stream temperature. We consider the BMP to be effective in this case. The dense woody vegetation is an important factor influencing the effectiveness of the RMZ.

E2: ROCK CREEK



PERIOD MONITORED (6-SEPT TO 25-SEPT 1990)

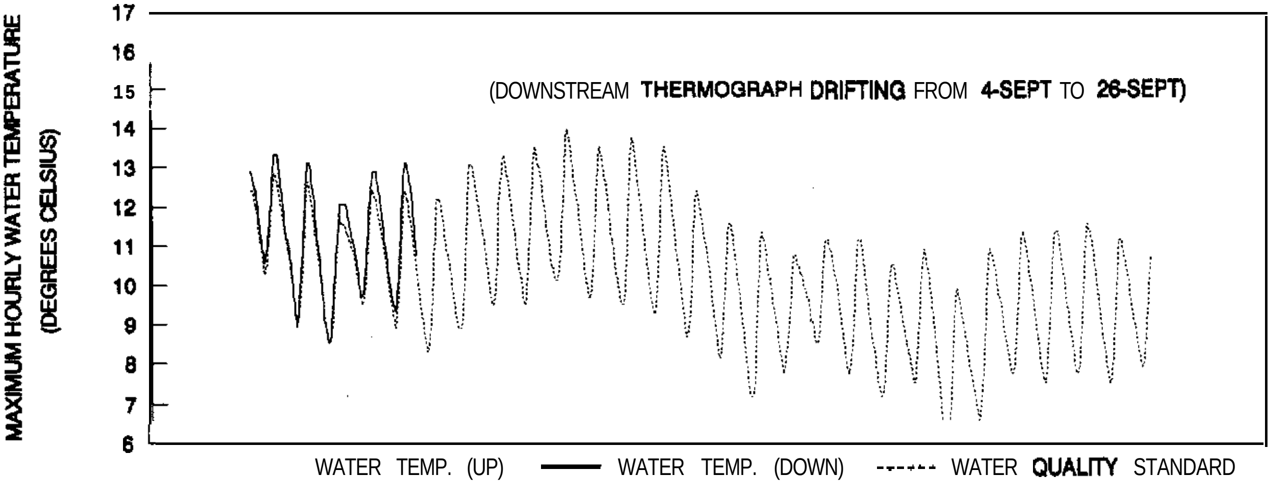
E3: Aeneas Creek

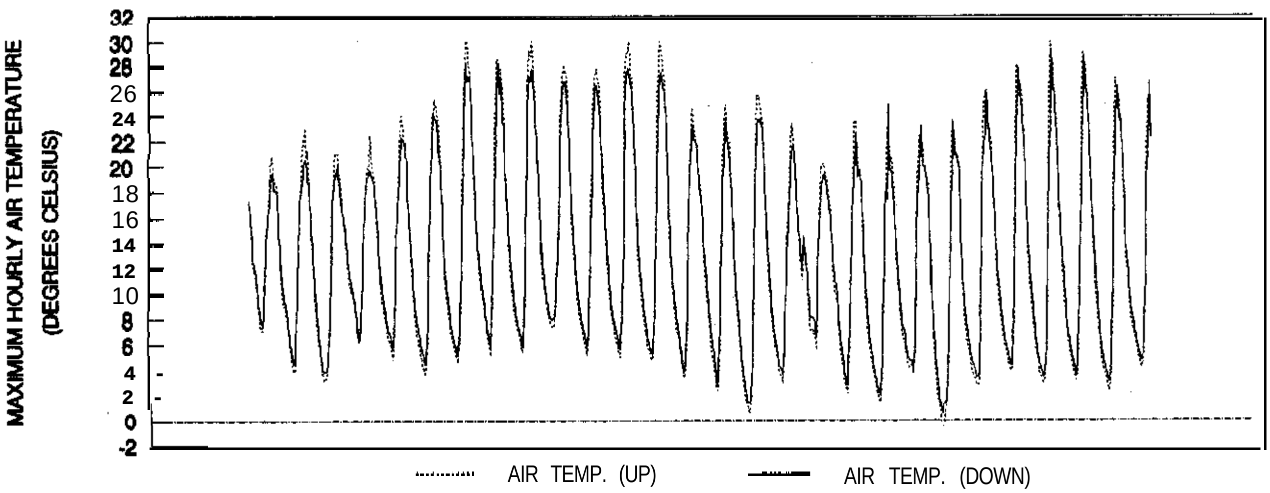
	Elevation	RMZ Shade	RMZ Width
BMP EFFECTIVENESS NOT DETERMINED	870 meters	Ave: 84% Range: 55-99%	Ave: 22.0 meters Range: 6.1-50.6 meters

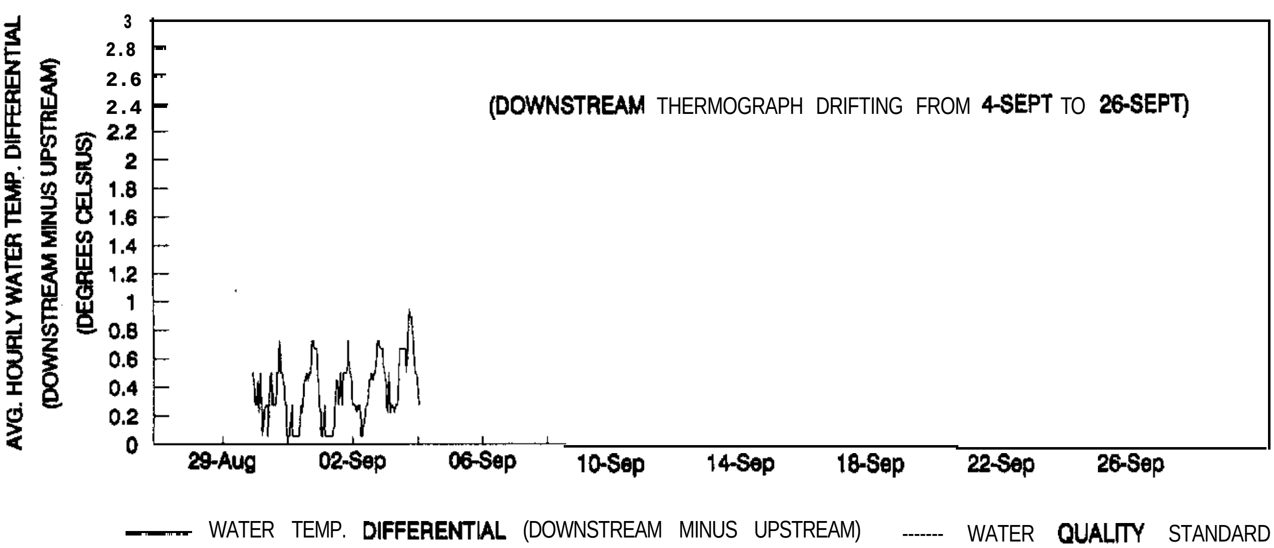
The two-sided RMZ along Aeneas Creek (Class AA) is located in central Okanogan County. This is a partial cut harvest unit. 'There is mature standing timber for at least 600 meters upstream of the study reach.

This site was monitored from August 29 to September 26. However, instrument drift was a problem with the water thermistor at the downstream site after September 3. From August 29 to September 3, Aeneas Creek did not exceed water quality criteria. However, the highest two day average air temperature recorded at the Tanasket weather station (about 28 kilometers northwest of the site) during the August 29 to September 3 period was 12°C below the highest mid-summer two day average. This indicates a substantial deviation from critical temperatures for this area. Therefore, it is unknown whether the conditions within this RMZ meet either criterion of the water quality standard.

E3: AENEAS CREEK







PERIOD MONITORED (29-AUG TO 26-SEPT 1990)

E4: South Fork Deep Creek

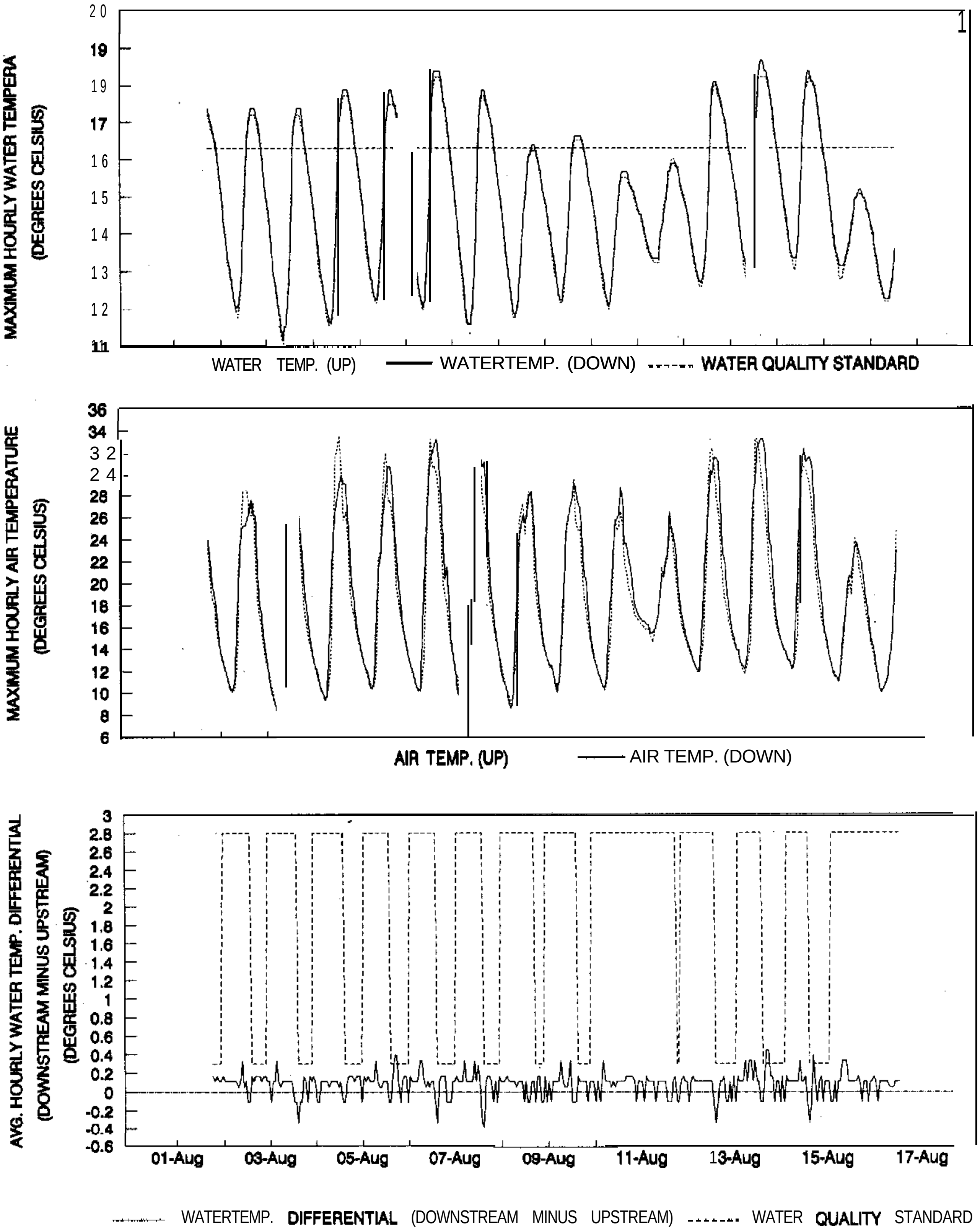
	Elevation	RMZ Shade	RMZ Width
BMP CONSIDERED EFFECTIVE	640 meters	Ave: 71% Range: 50-90%	Ave: 9.8 meters Range: 6.1-19.8 meters

This one-sided RMZ is associated with a partial cut unit in northern Stevens County on the west side of South Fork Deep Creek, a type 1, Class AA stream. The land opposite the RMZ is in standiig timber within the riparian zone, changing to rangeland with sparse timber on the uplands. There is standing timber upstream from the study reach on both sides of the stream for about 300 meters. Above this, the south side of the stream is in standing timber, while land on the north side is partially cut for a distance of about 300 meters, with standing timber above that. The amount of streamside woody vegetation was the highest of all 13 study sites (average of 2618 stems per hectare).

Monitoring took place from August 1 to August 16. The Class AA maximum allowable water temperature criterion (16.3°C) was exceeded on 12 of the 15 days at the downstream site and 11 days at the upstream site. The maximum daily water temperature differential (downstream minus upstream) ranged from only 0.2 to 0.4°C. However, on days when the upstream temperature (assumed to represent natural conditions) exceeded 16.0°C, the criterion for maximum allowable change due to timber harvesting would be 0.3°C. This criteria was slightly exceeded on four days.

Since we do not know what the stream shading conditions or temperatures were before harvest, we do not know whether leaving additional shade over the stream would have been possible in order to ensure that stream temperature did not increase through the RMZ. However, the observed increases are small enough to be accounted for by factors other than riparian shading or timber harvesting, such as a change in channel characteristics or measurement error. Therefore, we do not attribute exceedances of the temperature criteria to a lack of BMP effectiveness. This RMZ is considered effective because it does not appear that the harvest caused an increase in water temperature.

E4: SOUTH FORK DEEP CREEK



PERIOD MONITORED (l-AUG TO 16-AUG 1990)

DISCUSSION

In the previous section, the factors influencing BMP effectiveness were discussed in the context of individual case summaries. In this section, the collective data set is analyzed using three approaches to evaluate the influence of various factors on the effectiveness or ineffectiveness of the BMPs (i.e. RMZ regulations) as implemented at the study sites. First, the study sites were grouped according to BMP effectiveness and examined for influences that the overall setting of the harvest units or any site-specific anomalies may have had on RMZ effectiveness. Second, a principle components analysis was used to explore interrelationships among the various factors. And finally, we examined correlations between certain site variables and temperature parameters using scatter plots and linear regressions. This included an evaluation of physical site factors which conceptually have a direct or indirect influence on the physics of stream heating. For a more in-depth discussion of such factors and theory regarding stream heating in the context of a larger forest stream data set, see Sullivan et al. (1990). The current study examines many of the same factors with the limitation of a smaller data set, but witb the advantage of an additional parameter: the temperature change that occurred across the RMZ.

Study Site Comparisons

In terms of BMP effectiveness, the study sites were categorized in one of two ways: 1) sites where the BMP was judged to be effective at achieving water quality standards; and 2) sites where the BMP was judged to be ineffective at achieving water quality standards. The first category includes Tributary to Trap Creek, New Pond Creek, Indian Creek; Rock Creek, and South Fork Deep Creek. The second category includes Tributary to Pioneer Creek, Black Creek, North Fork Rabbit Creek, South Fork Ohop Creek, Bear Creek, and Tokul Creek. Aeneas Creek and Griffin Creek were not included in the above categories because no determination was possible regarding compliance with temperature criteria. The study site comparison is summarized in Table 4.

Table 4: Study Site Comparison

Site factors associated with BMP effectiveness

Effective BMPs	Ineffective BMPs
◆ High Shade Levels/Abundant Woody Veg.	◆ Low to Moderate Shade Levels
◆ High Elevation (> 600 meters)	◆ Low to Moderate Elevation (<500 meters)
◆ Relatively Wide RMZs	◆ Relatively Narrow RMZs
◆ High Gradient Streams	◆ Low Gradient Streams
◆ Substantial Groundwater Inflow	◆ Loss of Flow within Reach
◆ Partial Cut Harvest Units	◆ Beaver Activity
	◆ Harvest and/or Clearing Woody Veg. within RMZ
	◆ Clearcut Harvest Units

Sites Where The BMP Was Effective

Common characteristics among sites where the BMP was effective are high elevation and/or high shade, relatively wide RMZs (in three cases) and high gradient streams. The relatively high gradient of these streams (ranging from 2.3% to 8.096, with four of the five streams exceeding 3.5%) results in channel morphology which generally lacks slow, deep pools. High stream gradients may be related to relatively short residence times for water within the RMZ. Although four of the five RMZs in this category were one-sided, we do not believe that this is an important factor in BMP effectiveness since in each case the other side had a disturbed riparian zone due to previous land management.

Three of the five effective RMZs were above 600 meters in elevation. The two low elevation RMZs in this category both had high average shade levels (95%). Also, in the case of Tributary to Trap Creek, the substantial proportion of groundwater inflow probably influenced BMP effectiveness. The RMZs along Tributary to Trap Creek, New Pond Creek, and Indian Creek were wider than the average in this study. Whiie the RMZ on Rock Creek was the narrowest in the study (average width 8.8 meters), a dense growth of woody vegetation effectively shaded the stream. All three of the east side, partial cut RMZs for which we were able to determine BMP effectiveness are in this category.

Sites Where The BMP Was Ineffective

The six sites where the BMP was judged to be ineffective share certain characteristics which appear to have a strong influence on observed temperature conditions. Four of these sites were relatively low elevation (80 to 245 meters), while two were moderate elevation sites (425 to 465 meters). Average mid-channel shade was low to moderate (23% to 67%) in four of the six sites, while it was moderately high (82% to 91%) at the other two. The latter two sites are distinctive in that both are Class AA streams with more stringent temperature criteria. We believe that both of these sites could have benefitted by leaving more shade. Although the average level of shade was moderately high at these two Class AA sites, portions of the RMZs were fairly open. Three of the sites in this category had relatively narrow RMZs. Average RMZ width at all six sites was above the minimum and, at all but one study reach, below the maximum specified by the BMP. In all but one of the six, portions of the RMZs were very narrow (four meters or less) according to the Department of Wildlife measurements. All six of the sites where the BMP was ineffective are west side RMZs associated with clearcut harvest units.

Among the six sites where the BMP was judged to be ineffective are three low gradient streams (0.6 to 1.2%). Two of these had considerable beaver activity resulting in wide, deep pools with some open water segments. Even with these two, however, we believe that additional temperature control from shading would have been possible. This is based in part on observed background temperature conditions; in both cases the unharvested reach immediately upstream of the study RMZ had similar beaver activity and stream morphology, yet cooler temperatures. We observed considerably more woody vegetation in these undisturbed upstream reaches, which we believe can be important in providing effective shade. This contrasted with the more open appearance of the RMZs. Clearing of nonmerchantable woody vegetation to facilitate certain logging systems may be an important factor influencing temperature control on beaver streams and other sensitive streams.

The ineffective BMP category includes the deepest stream channels, based on average bankfull depth. There are three one-sided and three two-sided harvest units in this category. Two of the one-sided harvest units had standing timber on the opposite bank, a situation which would be expected to ameliorate increases in stream temperature associated with the timber harvest. With Black Creek, forest practices on the other side of the stream probably limited the effectiveness of the RMZ, as the riparian vegetation was rather sparse opposite the study RMZ. One of the sites in this category had considerable blowdown before the unit was harvested. This site also had a substantial number of trees harvested within the RMZ, due to perceived risk of future windthrow.

For sites in the ineffective category, we believe that increased levels of post-harvest shade would have enhanced BMP performance, resulting in achievement of water quality standards. In cases where the stream is highly temperature sensitive (e.g. North Fork Rabbit Creek), the only way for the BMP to be effective at achieving water quality standards is to ensure that the timber harvest does not remove any shade that provides temperature protection for the stream. There are two possible ways that the level of shade at sensitive sites can be maximized to the degree necessary for temperature protection: 1) leave a wider RMZ, or 2) do not harvest shade trees or otherwise remove vegetative shade within the RMZ. For all but two of the sites in this study where additional temperature protection is called for, there was no evidence that a substantial number of trees were harvested from within the RMZs. In these cases, we believe a wider RMZ, and/or retaining all non-merchantable woody vegetation, could have been a more effective BMP. Depending on local topography and the composition of the riparian canopy, the crowns of tall trees outside of the RMZ perimeters can potentially provide stream shading. In some cases where a wider RMZ is needed to retain stream shading, we believe it may need to be wider than the maximum width specified in the Forest Practice Rules for west side RMZs.

In four of the six sites where the BMP was ineffective, site specific anomalies (e.g. beaver activity, significant loss of flow) were primary factors in the performance of the BMP. Forest managers should recognize that the proposed new TFW temperature method (Doughty, *et al.*, 1991) is not designed to directly address such site specific anomalies. However, the proposed method for identifying temperature sensitive streams and designing RMZs does take into account two of the most important factors influencing the overall temperature regime of forest streams: site elevation and post-harvest shade.

Influence of the Water Qualitv Standards Classification

In at least one of the thirteen study sites (Ohop Creek), the water quality standards classification is an administrative factor, influencing the determination of BMP effectiveness.

The current system of determining the standards classification is based largely on either land ownership and land use or the classification of downstream waters. For example, streams are Class AA within the boundaries of National Parks and National Forests, and then become Class A downstream of such boundaries. Elsewhere, a stream is Class AA if it is a tributary to a lake or another waterbody which has been specifically classified as AA. While this classification system is appropriate for designating beneficial uses and assigning certain water quality criteria, it is not always meaningful for the purposes of assigning stream temperature criteria. The result is temperature criteria which in some cases are not representative of the natural temperature conditions of streams.

From the standpoint of the physical factors influencing stream temperature, a more appropriate way to classify streams for temperature criteria would be a system that accounts for differences in ambient air temperature, groundwater inflow, and channel characteristics which affect the physics of heat gain and loss in a stream under natural conditions. For example, a classification system based on a combination of elevation, stream order, and ecoregion might be appropriate. Elevation would account for ambient air temperature regimes, while stream order would address the physical dimensions of a stream (which in turn affect its response to heat inputs and the effectiveness of riparian shading). Stream order may also relate in a general way to the relative proportion of groundwater inflow. An ecoregion approach could account for differences in climate and hydrology.

The current classification system, while not always consistent with naturally occurring temperature conditions, establishes criteria which are intended to be protective of beneficial uses. The criteria recognize that natural conditions may result in temperatures above tbe criteria, and in such cases allow essentially no increase due to human activity. This system results in a higher performance standard for BMPs in certain drainages. The intent of the classification system is to provide an adequate level of protection for downstream Class AA streams or lakes potentially affected by the pollutant loads of their tributaries. While it is important to provide an extra measure of protection for downstream waters where conservative pollutants are concerned, stream temperature in forested areas is primarily influenced by local environmental conditions (including those immediately upstream) which control the thermal equilibrium.

Principal Components Analysis

A principal components analysis (PCA) was used to evaluate relationships among the study sites and various site characteristics. Analyses were performed using Systat© software. PCA is a multivariate ordination procedure which may be used to reduce a multi-dimensional swarm of data into two or three dimensions to facilitate observations of relationships between data points. In PCA, a series of axes are identified which describe the intrinsic structure of the data swarm. The first principal component may be thought of geometrically as the axis which explains as much as possible of the variability *in* the relative placement of the original set of data points (Jackson, 1983). The second principal component is tbe axis, perpendicular to first principal component, which best explains the remaining variability, and so on. In algebraic terms, the first principal component may be described as the linear function which best explains the variation within the original data set.

In our use of PCA, we plotted the thirteen study sites according to the first two principal component axes. The result is shown in Figure 2. Of the eighteen variables used in the PCA, several were found to be important in the first and/or second principal component, and these are used to label the four quadrants of the plot. The first principal component explained 41% of the variability in the original data, and was most heavily weighted by air temperature, water temperature, monitoring date, stream gradient, stream depth, elevation, shade, and stream width, in that order. The second principal component explained an additional 16% of the variability, with the heaviest weight given to tree count, elevation, distance to divide, stream depth, and gradient. RMZ length, RMZ width, and stream orientation were not weighted heavily in either of the first two principal components, but were the dominant variables in the third principal component, which explained an additional 14% of the variability in the original data.

Sites which plot near each other in Figure 2 have similar scores based on the eighteen variables considered, and are related in terms of these two principal components. We find some of the groupings apparent in Figure 2 interesting. Sites W2, W3, and W8 are all low gradient streams where the BMP was ineffective, and bothW2 and W8 were heavily influenced by beavers. Sites W7 and E2 plot very close together and represent two of the five streams where the BMP was effective. Another site where the BMP was effective, W1, is located similarly to W7 and E2 with respect to the first principal component but dissimilarly with respect to the second, largely due to its low elevation and high gradient.

The loadings of the variables used in the PCA establish the amount of weight they have in the principal components. These loadings may also be plotted with respect to the principal components axes to depict interrelationships among the variables. We found that air temperature and water temperature were strongly related to each other, but inversely related to shade and monitoring date, with a somewhat weaker inverse relationship to elevation, gradient, and tree count. There was a strong positive relationship between elevation and tree count, and a somewhat weaker positive relationship between stream depth and stream width. Stream gradient was inversely related to stream depth and width. The relationships explained in the PCA support many of the observations made in the study site comparisons and case summaries.

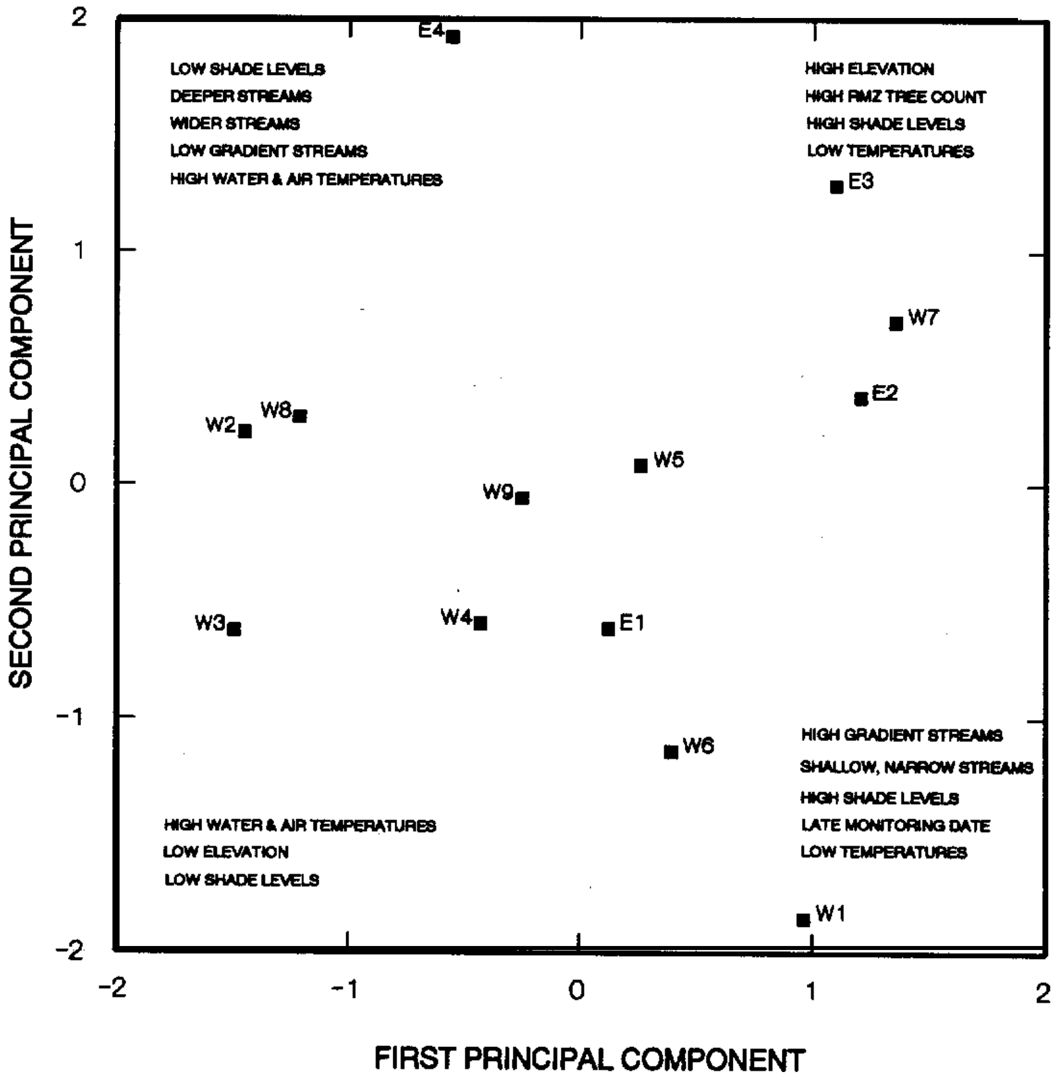


Figure 2: Principle Components Plot of the 13 Study Sites

Linear Regressions

Relationships among various site factors and observed stream temperature parameters were explored further using scatter plots and linear regressions. Regressions were run using Systat© software. Selected scatter plots with regression results are presented in Appendix C. The relationships examined are discussed below. Unless otherwise noted, regression coefficients for the independent variables were significant at or above the 95% level (i.e. we are at least 95% certain that the coefficients are significantly different from zero).

Effect of Monitorine Date

The date of monitoring appears to have a strong influence on observed stream temperature regimes. This is illustrated by the negative correlation between median Julian date of monitoring and the median of maximum daily water temperature ($r^2=0.56$). The median Julian date was also correlated with the median of maximum daily air temperatures ($r^2=0.73$). Julian date was not correlated to stream temperature change (downstream minus upstream temperature). The medii Julian date of monitoring may be thought of as a variable which integrates such influential factors as air temperature and solar angle.. It is important to recognize the influence of the monitoring period as other correlations are explored. The wide variation in the dates of monitoring, with only a few of the sites monitored during periods of critical temperature conditions, probably distorts some of the relationships between physical site factors and temperature.

Air Temperature

Air temperature was positively correlated with water temperature. Regressions of the median of daily maximum air and water temperatures, with air as the independent variable, resulted in an r^2 of 0.56 using data from the downstream thermograph sites and 0.39 using data from the upstream (background) thermograph sites. When maximum air and water temperatures were used, r^2 was 0.51 and 0.53, respectively, for the downstream and upstream monitoring sites. Air temperature showed no significant correlation to water temperature change between upstream and downstream monitoring sites.

The lack of a positive correlation between air temperature and stream temperature change is somewhat counter-intuitive. However, it is consistent with our observation that significant stream heating occurred in some RMZs where the background air temperatures were warmer (or at least not significantly cooler) than downstream air temperatures. Direct solar heat input to the stream at various points along the RMZ may be an important factor that is not reflected in near-stream air temperature measurements taken at the thermograph sites. We believe that direct solar heating, through localized openings in the riparian canopy or where the stream is aligned with the midday solar azimuth, could be especially important in low gradient streams (e.g. beaver streams) due to the water's longer residence time.

Elevation

Site elevation is a primary controlling factor for stream temperature, largely because of the relationship of elevation to air temperature regimes. Using simple linear regression, elevation at the RMZ midpoint was negatively correlated to maximum downstream water temperature ($r^2=0.37$) and to the median of maximum daily water temperature ($r^2=0.36$). The correlation between elevation and maximum water temperature. at the upstream monitoring sites was somewhat weaker ($r^2=0.31$, significant at the 90% level). Site elevation was similarly correlated with maximum air temperature at the downstream sites ($r^2=0.35$). There was essentially no correlation between site elevation and water temperature change between upstream and downstream monitoring sites.

We find it interesting that elevation, which has a strong theoretical relationship to stream temperature, explained only 37% of the variation of maximum water temperature in this data set. This points out the importance of other factors. When shade was added as an independent variable along with elevation in multiple regression, 51% of the variation in maximum water temperature was explained, although the regression coefficient for shade was not significant at the 95% level ($p=0.12$). When Julian date and elevation were used as two independent variables in multiple regression, 70% of the variation in maximum temperature was explained.

Riparian Shade

Shade over the stream is a key factor for temperature control in forest streams, because it is something that can be managed. With this set of data, average shade was negatively correlated with water temperature. By itself, however, shade did not explain a substantial amount of the variation in maximum water temperature ($r^2=0.22$), and the regression coefficient was not significant at the 95% level ($p=0.11$). As mentioned above, the r^2 is 0.51 when both shade and elevation are used as independent variables in multiple regression. The relationship of maximum observed temperatures to average shade and site elevation is illustrated graphically in Figure 3. The data from Tributary to Trap Creek is an outlier in this plot, which may be explained partly by the influence of groundwater inflow and partly by the lateness of monitoring at this site. Average shade was not correlated to maximum air temperatures. This is consistent with our observations that recorded air temperatures were sometimes higher at the background sites, despite the greater level of shading at these sites.

In this study, shade levels among the RMZs are compared using the average of shade measurements made at a number of points within the individual RMZ. Likewise, the individual shade measurements are averages of four directional measurements. While useful for comparisons between sites, these average RMZ shade figures may not always reflect the critical riparian shade conditions influencing stream temperature. In some of our study sites the individual point measurements of shade are relatively uniform while in others the measurements are highly variable. There is also a directional component to stream shading that is masked by the average shade figures. We believe that for some of the sites monitored

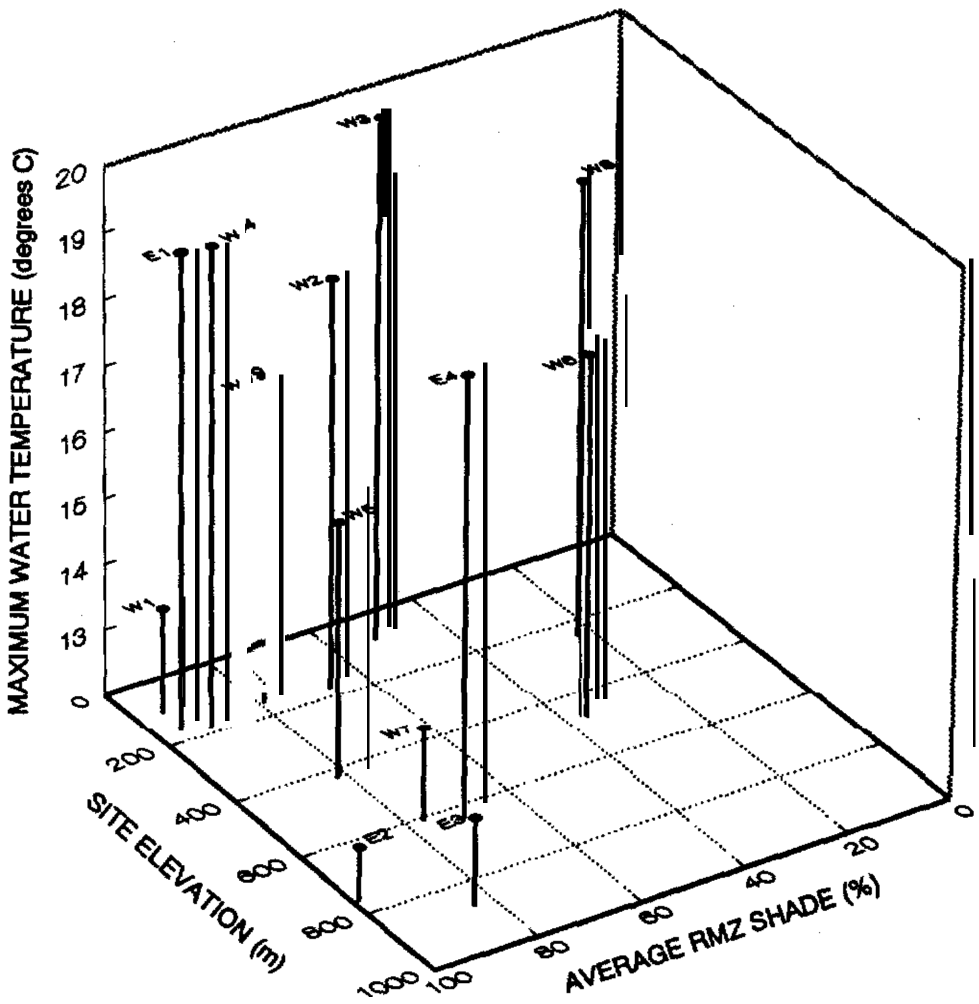


Figure 3: Relationship of Shade and Elevation to Maximum Water Temperature

in this study, site specific conditions within the RMZ (e.g., a midday opening above the stream that aligns with the solar azimuth or open portions of an otherwise well-shaded RMZ) may override the effects of a high average shade level.

Groundwater Influence

Groundwater inflow can have **a significant** influence on stream temperature regimes **(Mackey** and **Berrie,** 1991; Sullivan et ***al.,*** 1990). The influence of substantial amounts of groundwater inflow on stream temperature is strong because groundwater is generally cooler than surface water during the summer months. Sullivan et al. (1990) suggested that the temperature of groundwater in an area is similar to the annual average air temperature, which ranges from about 9.0 to 11.0°C within our study areas. During summer baseflow, essentially all of the flow in a given stream reach is contributed by groundwater inflow either in that reach or upstream from it. After the groundwater enters the channel it begins to establish thermal equilibrium with surface conditions, until eventually its cooling effect on the stream is diminished. Conceptually, stream reaches with a high proportion of groundwater inflow would be cooler than otherwise, and less responsive to heat inputs due to reduced riparian shading.

We used simple linear regression to test the relationship between groundwater inflow and stream temperature. The independent variable accounting for groundwater influence was the ratio of discharge at the downstream end of the monitored reach to discharge at the upstream end, referred to as Q-ratio. The comparison of discharge estimates gives a rough approximation of groundwater gain or loss within the RMZ reach. A Q-ratio greater than 1.0 indicates the reach is gaining groundwater, while a Q-ratio less than 1.0 indicates a losing reach. The dependent variable was median of maximum daily temperature change (downstream temperature minus upstream). As expected, Q-ratio was negatively correlated with temperature change ($r^2 = 0.32$, significant at the 90% level). Sites with proportionately greater groundwater inflow had lower increases in temperature. There was no significant correlation between Q-ratio and maximum water temperature. Groundwater influence was most apparent in North Fork Rabbit Creek (Site W4 on the correlation plots). Data from this site are outliers in many of the correlations using temperature change.

Stream Azimuth

There is a conceptual relationship between stream orientation and temperature sensitivity, as this relates to the time of day and solar angle when the solar azimuth is aligned with the stream azimuth. Two approaches were taken to evaluate this relationship. First, azimuths were converted to O-90 degree bearings for regression analysis. For our data set, there were no significant correlations between azimuth and any of the temperature parameters.

Second, maximum stream temperatures were plotted by stream azimuth (facing downstream). This plot is presented in Appendix C. There are seven sites in the two north-south oriented quadrants, with an average maximum temperature of **17.6°C.** There are five sites within the west facing quadrant, 'with an average maximum temperature of 16.2°C. However, when sites located within 10 degrees of the quadrant boundaries are excluded, and the sites with the strongest north-south orientation are compared to those with the strongest east-west orientation, the average maximum temperatures are almost identical. The three streams that had south-southwest orientations demonstrated high temperatures, with maximums exceeding 18.0°C in each case. Other than this grouping, there does not appear to be any consistent relationship between stream orientation and maximum stream temperature in this data set. However, we believe that on a site specific basis, stream orientation in relation to the solar path could be an important consideration when designing an RMZ to maximize midsummer shade on a temperature sensitive stream.

Stream Depth

Average bankfull depth was positively correlated with the median of maximum daily water temperature ($r^2=0.37$) and with maximum water temperature ($r^2=0.41$). There were no significant correlations between bankfull depth and the temperature change parameters. Average water depth at the thermograph sites showed no correlation with the temperature parameters.

Stream Gradient

Stream gradient was negatively correlated to maximum water temperature ($r^2= 0.24$) and to the median of daily maximum water temperatures ($r^2=25$). In both of these regressions, the coefficient was significant at the 90% level. While the correlation is not strong, the inverse relationship is consistent with our observations that gradient may be a factor influencing BMP effectiveness. There was no significant correlation between gradient and measured temperature change.

Bankfull Width

Average bankfull width was not significantly correlated with any of the temperature parameters. Bankfull width was negatively correlated with average shade, explaining 37% of the variability in shade among the sites.

other Factors

There was no correlation shown by linear regression between the site characteristics of distance to divide, average RMZ width, or tree count/hectare and any of the temperature parameters. Average RMZ width showed a weak positive correlation to shade with this data set, explaining 21% of the variation in average RMZ shade, but the correlation coefficient was not significant at the 95% level ($p=0.12$). Tree count did not correlate with shade, although one might expect some relationship between these variables. For the streams in this study, distance to divide was not correlated to the channel characteristics of average bankfull width or average bankfull depth, although one might expect a positive correlation between these variables.

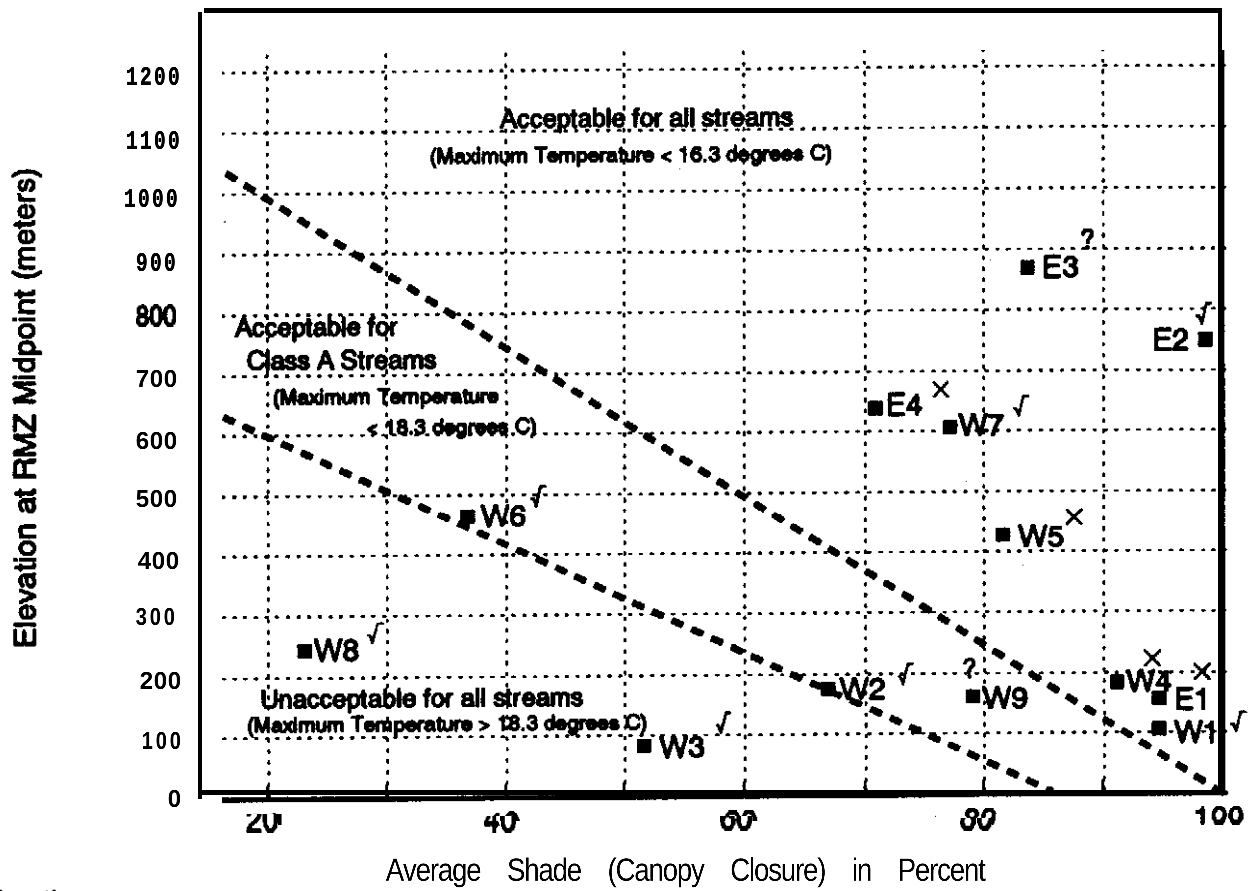
Proposed New TFW Temperature Method

As discussed earlier, previous work by the TFW Temperature Work Group resulted in the development of a proposed new method for identifying temperature sensitive streams and designiig RMZs. We applied the tools (screen and model) from the proposed method to our study sites and compared the results to our conclusions about the effectiveness of the study RMZs. This comparison is not intended to be an exhaustive test of the proposed method. The 13 study sites are plotted on the temperature screen in Figure 4. Of the 11 sites where we have determined whether the criteria for maximum temperature are met, the screen correctly identifies the temperature category for seven of the sites, or 64 % . This includes sites W2 and W6 that plotted on the dividing line. These two sites are marginal, but we concluded that they are possibly exceeding criteria.

Four of the eleven were incorrectly placed in the "acceptable for all streams" category, including three which definitely exceeded criteria and one (W5) which we judged as possibly exceeding criteria. We note that temperatures at W5 were marginal, and that two of the four "false positives" are anomalous in that they are losing stream reaches. It is also interesting that three of the four are Class AA streams. Our results do not allow us to test whether the screen correctly identifies the temperature category for sites W9 and E3. Considering the site specific anomalies at sites W4 and El, and the marginal nature of site W5, we believe the screen performed well. If the two sites with flow loss were excluded, the screen would correctly categorize 78% of our sites.

The TFWTEMP model is another tool that is used in the proposed method. The model relies on user supplied site information and internally generated information to predict maximum, mean, and minimum stream temperatures. We compared our measured maximum stream temperatures to those predicted by the model. The model correctly identified the maximum observed temperature 77% of the time to $\pm 3.0°C$, 62% of the time to $\pm 2.0°C$, and 15% of the time to $\pm 1.0°C$. The model includes an option which recalculates stream temperature using a safety factor to account for higher air temperatures. Using this option, the model correctly identified the maximum observed temperature 77%, 54%, and 23% of the time for accuracies of $\pm 3.0°C$, $\pm 2.0°C$, and $\pm 1.0°C$, respectively. The model underestimated the maximum stream temperature 69% of the time and overestimated it 31% of the time. The largest prediction errors ($> 3.0°C$) were made in the case of sites W4 and El, two losing stream reaches, and site E4.

The TFWTEMP model also indicates whether the proposed post-harvest shade level is acceptable or not in consideration of stream classification and water quality standards. Of the 11 sites where we have determined whether the criteria for maximum allowable temperature are met, the model correctly identified two as "unacceptable" and three as "acceptable". The model incorrectly identified six of the sites we determined to be



Explanation:

√ = Site plotted in correct category based on our assessment of whether waler quality standards were exceeded (see Table 1).

x = Site plotted in incorrect category based on our assessment d whether water quality standards were exceeded (see Table 1).

? = Unknown whether site plotted in correct category; we could not determine whether water quality standards were exceeded.

Figure 4: TFW Temperature Screen Applied to the 13 Study Sites

exceeding or possibly exceeding criteria as "acceptable". Two of the six incorrectly identified sites are losing streams, a situation not addressed by the model. The model's calculations assume a positive groundwater inflow rate. Another of the six is a beaver stream for which the model greatly underestimated stream depth. We note that two of the sites incorrectly rated as "acceptable" by the model are marginal cases where we observed maximum temperatures within ±0.5°C of the criteria.

Based on our limited evaluation; we believe that there is a problem with the way in which the model selects air temperature profiles for use in its calculations. Although we did not monitor during critical summer conditions in many cases, we recorded air temperatures which were considerably higher than those used by the model in its calculations. For our study sites, which represent a fairly wide range of climate regions and elevations, the model chose only air temperature profiles number 1 and 2. These profdes correspond to maximum July 15 to August 15 air temperatures of 189°C and 20.9°C, considerably lower than maximum air temperatures recorded at our monitoring sites. It is likely that the accuracy of the model can be improved considerably by modifying the selection of air temperature profiles. Since it relies heavily on empirical relationships to generate many of the values used in its calculations, the model is designed to be improved through incorporation of new data.

We believe the proposed new method is capable of correctly identifying temperature sensitive streams in a majority of cases. However, the screen and model may not adequately identify streams which are sensitive due to site specific anomalies such as flow loss and modification by beavers. In predicting temperature categories (*i.e.* acceptable vs. unacceptable), the *screen* performed better than the model for our data set. The proposed method relies heavily on the screen, with the model proposed for use only in cases where the possibility of exceeding the temperature change criterion of 2.8°C is indicated. Given this use of the model, it may not be critical that it correctly determines the acceptability of post-harvest shade levels, but rather that it can predict a change in water temperature associated with a change in shade levels when other factors are held constant.

The proposed new method, while having some limitations, offers major advantages over the current BMPs which rely on standard RMZ prescriptions and upgraded standard prescriptions for temperature sensitive streams. The main advantage of the proposed method is its incorporation of two of the primary factors affecting stream temperature: site elevation and riparian shade. Another important advantage is that the proposed new method ties the concept of temperature sensitivity directly to state water quality standards, whereas the current RMZ rules do not.

CONCLUSIONS AND RIXOMMENDATIONS

Conclusions

Based on the previous discussion and observations contained in the case summaries, we are able to draw a number of conclusions regarding BMP effectiveness and the factors which influence the ability of the current **RMZ** rules to achieve water quality criteria for temperature.

1) The RMZ prescriptions were effective at meeting water quality standards at five of the thirteen sites. This includes all three of the east side, partial cut harvest units for which we were able to determine BMP effectiveness. At two of these east side **RMZs,** maximum water temperatures exceeded the water quality criteria, but the exceedances were not attributed to *timber* harvesting. The BMP was effective at all three of the study sites which were above 600 meters elevation.

2) The **RMZ** prescriptions were ineffective at meeting water quality standards at six of the thii study sites. All of these were west side units with **clearcut** harvests, and all were below 500 meters elevation. For these sites we believe that leaving additional shade within the **RMZ,** or leaving a wider RMZ, could have resulted in achievement of water quality standards. The standards could have been met either through meeting the numerical criteria or assuring that there was no temperature increase associated with the harvest (i.e. no removal of trees or nonmerchantable woody vegetation that provide shade to the stream).

3) At the two remaining sites, we were. not able to determine BMP effectiveness due to the lateness of monitoring and the marginal nature of the results.

4) The primary site factors associated with effective **RMZs** appear to **be:** moderately high elevation (> 600 meters), high average levels of riparian shading, relatively wide **RMZs,** dense woody vegetation, groundwater inflow within the reach, stream morphology associated with relatively high gradients, and partial cut harvesting.

5) The primary site factors associated with ineffective **RMZs** appear to be: low to moderate elevation (< 500 meters); low to moderate levels of riparian shade; loss of streamflow within the **reach;** stream morphology associated with low gradients and/or stream modification by beaver activity resulting in wide, deep pools and open water segments; and **clearcut** harvesting. Removal of **nonmerchantable** woody vegetation appears to be an important factor in some **RMZs,** particularly in highly sensitive beaver streams.

6) The water quality standard classification that applies to a site is an administrative factor that influences the determination of BMP effectiveness by setting a higher performance standard for certain sites. **RMZs** designed for Class AA streams may need to retain more of the pre-harvest shade when other site characteristics indicate temperature sensitivity.

7) For study sites where additional shade was needed to achieve water quality standards, a wider RMZ (i.e. a wider leave tree perimeter) or retaining all of the trees and other woody vegetation within the RMZ would have been required. Harvesting within the leave tree perimeter of the RMZ was a factor which limited the effectiveness of the RMZ in at least two of the study sites.

8) In certain cases where streams are highly temperature sensitive, the only way to ensure BMP effectiveness is to design the RMZ such that no reduction in stream shading occurs. This contrasts with RMZ rules in effect at the time the study units were harvested, which called for retaining 50% to 75% of the pre-harvest shade level for temperature sensitive streams. We believe it may be necessary to retain 100% in some cases.

9) The minimum RMZ width of 7.6 meters (25 feet) for west side streams is inadequate for temperature protection on many moderate to low elevation streams. In some cases, the maximum RMZ width of 15.2 meters (50 feet) for west side type 3 streams may not be wide enough for adequate temperature protection. This could be the case in some situations where retaining 100% of the shade is called for to protect stream temperatures. Whether or not trees outside of the maximum RMZ width could provide effective shade would depend on the composition of the riparian stand and/or site topography.

10) The proposed new TFW method for identifying temperature sensitive streams and designing RMZs takes many of the important site factors into account, and is expected to identify streams requiring enhanced temperature protection (i.e. above-minimum RMZ prescriptions) in a majority of cases. The method may not identify streams which are sensitive due to site specific anomalies such as beaver activity or loss of flow. In marginal cases, where the screen does not yield a clear result in terms of acceptability, the only way to be certain whether the proposed shade removal is acceptable is to monitor stream temperature prior to harvesting during critical summer conditions.

Recommendations

1) Incorporate the proposed new TFW temperature method (temperature screen and TFWTEMP model) into the Forest Practices Rules. Modify the way in which the model selects air temperature profiles. Established a process to periodically update the empirical components of the screen and model as more data become available.

2) Include procedures for identifying and addressing site specific anomalies in the stream temperature method for designing RMZs. In addition to using the temperature screen and/or model, identification of temperature sensitivity should address site specific situations, such as stream modification by beavers and stream reaches which are losing flow, in order to adequately protect sensitive streams.

3) Add provisions in the **RMZ** rules for retention of 100% of stream shading for the most sensitive stream reaches. This should be required in all cases where pie-harvest conditions exceed maximum temperature criteria. All nonmerchantable woody vegetation should be retained on beaver streams and other temperature sensitive streams.

4) Consider revising minimum RMZ widths for low elevation, west side streams, and determine whether the maximum RMZ widths for west side, type 3 streams are adequate. This may require additional temperature monitoring in low elevation streams in conjunction with RMZ characterization.

5) Consider revising the water quality standards classification system for the purposes of temperature criteria in forest streams, in order to be more representative of naturally occurring temperature regimes.

6) In future studies of BMP effectiveness, monitoring of stream temperatures should be conducted during the July 15 to August 15 period to ensure results that are representative of critical stream temperature conditions (i.e. maximum equilibrium temperature). If feasible, monitoring before and after harvesting should be conducted to definitively determine whether the BMP is effective at meeting the criteria for temperature change.

REFERENCES

Barney, J., 1992. Personal communication with Unidata representative, March 25, 1992.

Brown, G.W. 1970. Predicting the effects of clearcutting on stream temperature. Journal of Soil and Water Conservation, 25:11-13.

Carlson, A. 1991. Characterization of Riparian Management Zones and Upland Management Areas with Respect to Wildlife Habitat, Project Database. Washington State Department of Wildlife. Olympia, Washington.

Currier, J.B. 1980. An Approach to Water Resources Evaluation of Non-point Silvicultural Sources, Chapter VII: Temperature. U.S. Environmental Protection Agency, Environmental Research Laboratory, Athens, Georgia. 29 pp.

Doughty, K., J.E. Caldwell and K.S. Sullivan. 1991. T/F/W Stream Temperature Method: Users Manual. Timber Fish/Wildlife Report No. TFW-WQ4-91-002. Washington State Department of Natural Resources. Olympia, Washington. 40 pp.

Mackey, A.P. and A.D. Berrie. 1991. The Prediction of Water Temperatures in Chalk Streams from Air Temperatures. Hydrobiologia, 210: 183-189.

Jackson, B.B. 1983. Multivariate Data Analysis, An Introduction. Richard D. Irwin, Inc. Homewood, Illinois. 244 pp.

Omemik, J.M. 1987. Ecoregions of the Conterminous United States. Annals of the Association of American Geographers. 77(1): 118-125.

Sullivan, K., J. Tooley, K. Doughty, J.E. Caldwell, and P. Knudsen. 1990. Evaluation of Prediction Models and Characterization of Stream Temperature Regimes in Washington. Timber/Fish/Wildlife Report No. TFW-WQ3-90-006. Washington State Department of Natural Resources. Olympia, Washington. 224 pp.

Unidata Australia. 1990. Starlog Product Catalogue 1990. Unidata Australia. Willetton, Australia. 26 pp.

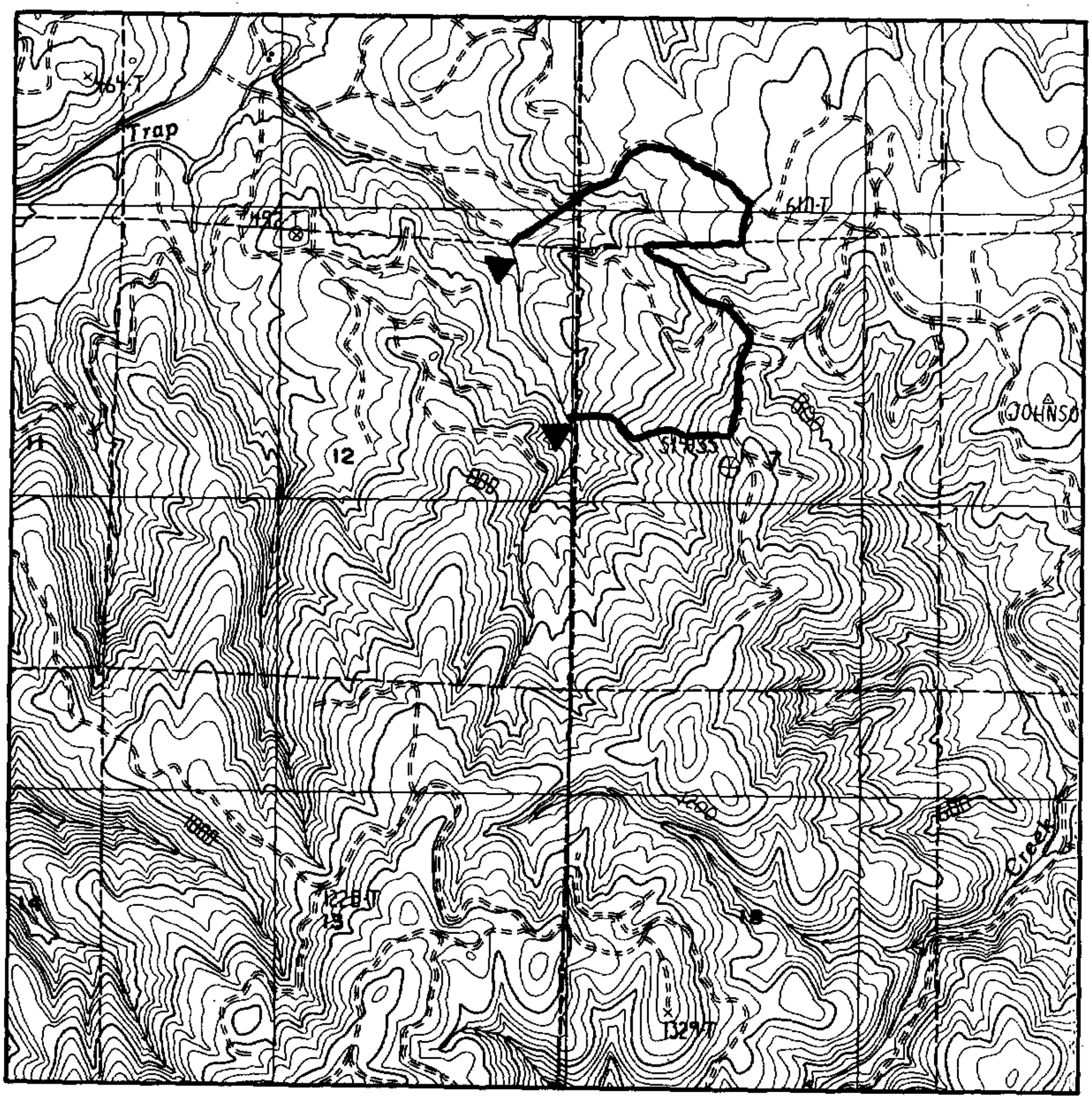
Washington Department of Wildlife. 1990. Characterization of Riparian Management Zones and Upland Management Areas with Respect to Wildlife Habitat, Field Procedures Handbook. Washington State Department of Wildlife/TFW Cooperative Monitoring, Evaluation, and Research Committee. Olympia, Washington. 19 pp.

APPENDIX B

MAPS OF THE STUDY SITES

T/F/W TEMPERATURE BMP EVALUATION PROJECT
1990 STUDY SITE

W1: TRIBUTARY TO TRAP CREEK



SCALE 1:24000

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1 .5 0 1 KILOMETER

CONTOUR INTERVAL 40 FEET

N

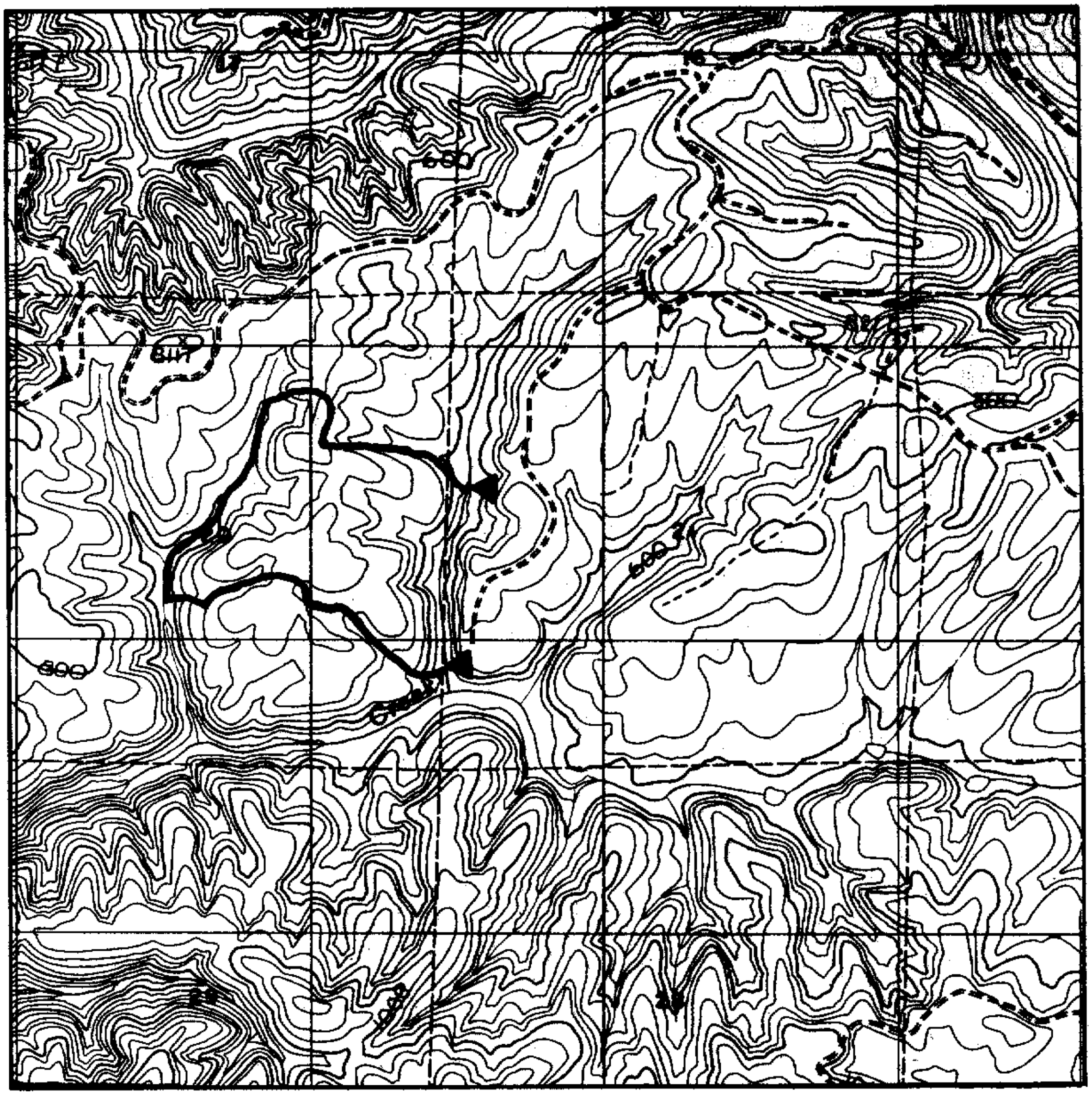
LEBAM
QUADRANGLE

▲ THERMOGRAPH SITE

HARVEST UNIT BOUNDARY

T/F/W TEMPERATURE BMP EVALUATION PROJECT
1990 STUDY SITE

W2: TRIBUTARY TO PIONEER CREEK



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1 .5 0 1 KILOMETER

CONTOUR INTERVAL 40 FEET

N

BLUE MOUNTAIN QUADRANGLE

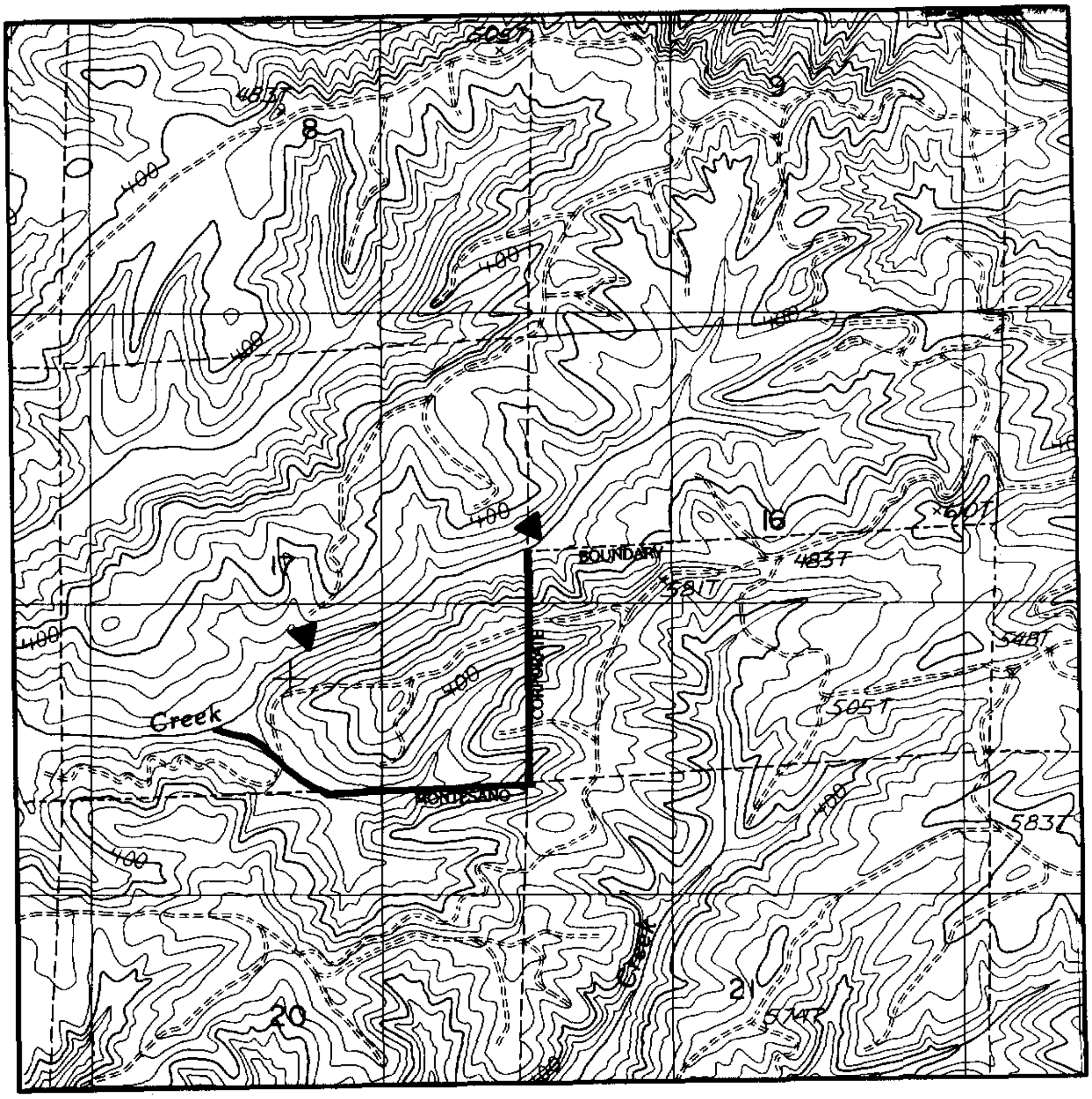
▲ THERMOGRAPH SITE

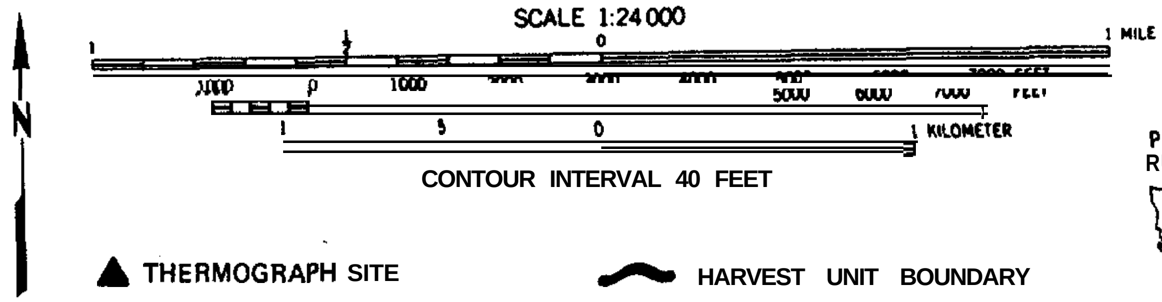
HARVEST UNIT BOUNDARY

1

T/F/W TEMPERATURE. BMP EVALUATION PROJECT
1990 STUDY SITE

W3: BLACK CREEK





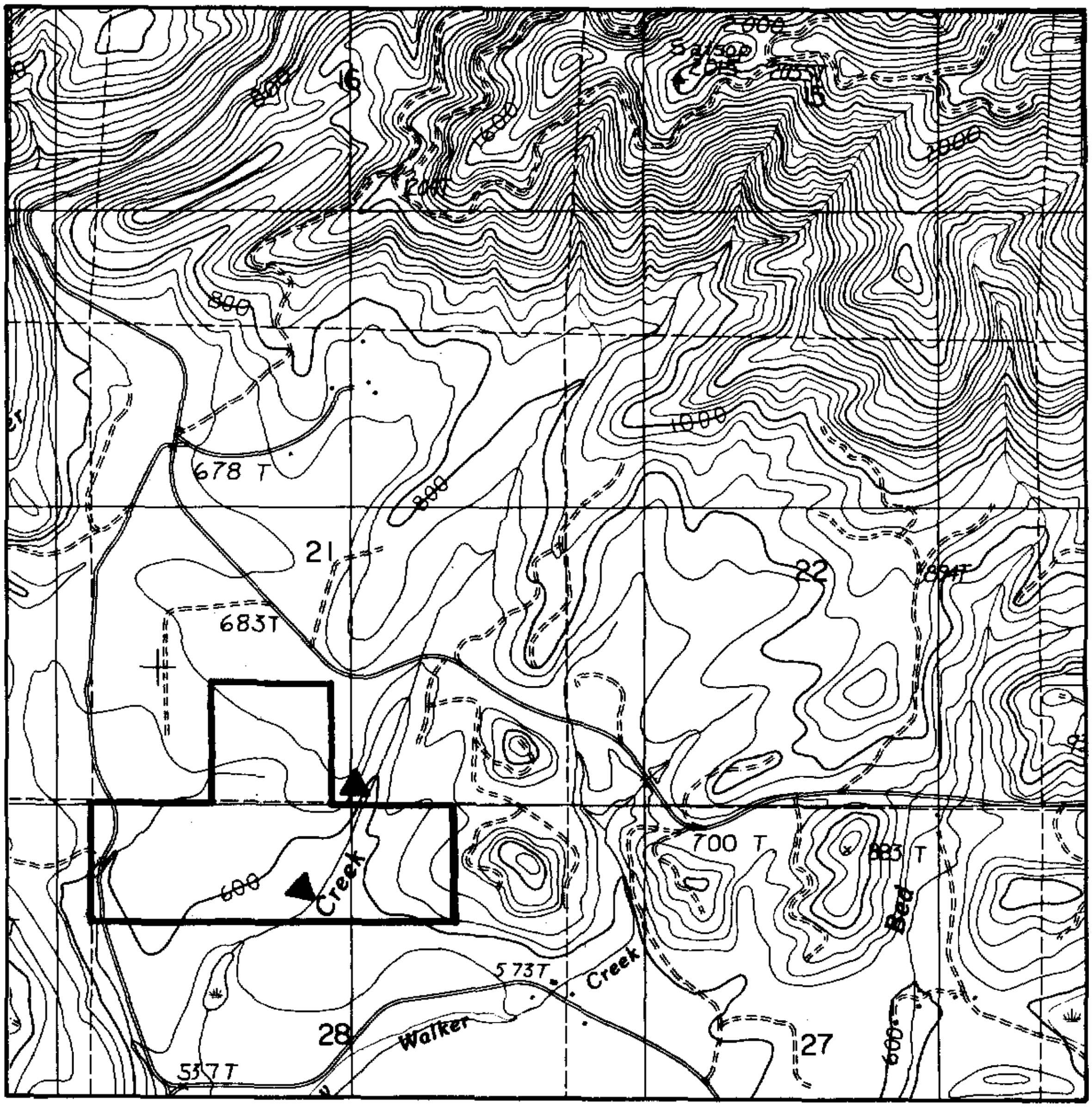
PRICES PEAK QUADRANGLE

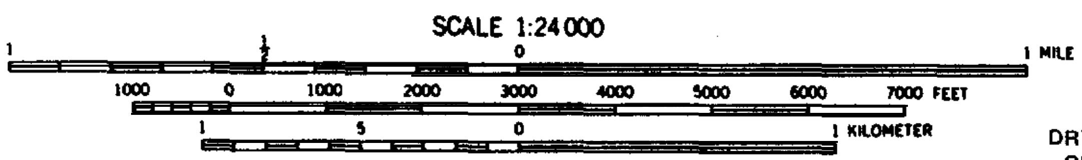
▲ THERMOGRAPH SITE

HARVEST UNIT BOUNDARY

T/F/W TEMPERATURE BMP EVALUATION PROJECT
1996 STUDY SITE

W4: NORTH FORK RABBIT CREEK





CONTOUR INTERVAL 40 FEET

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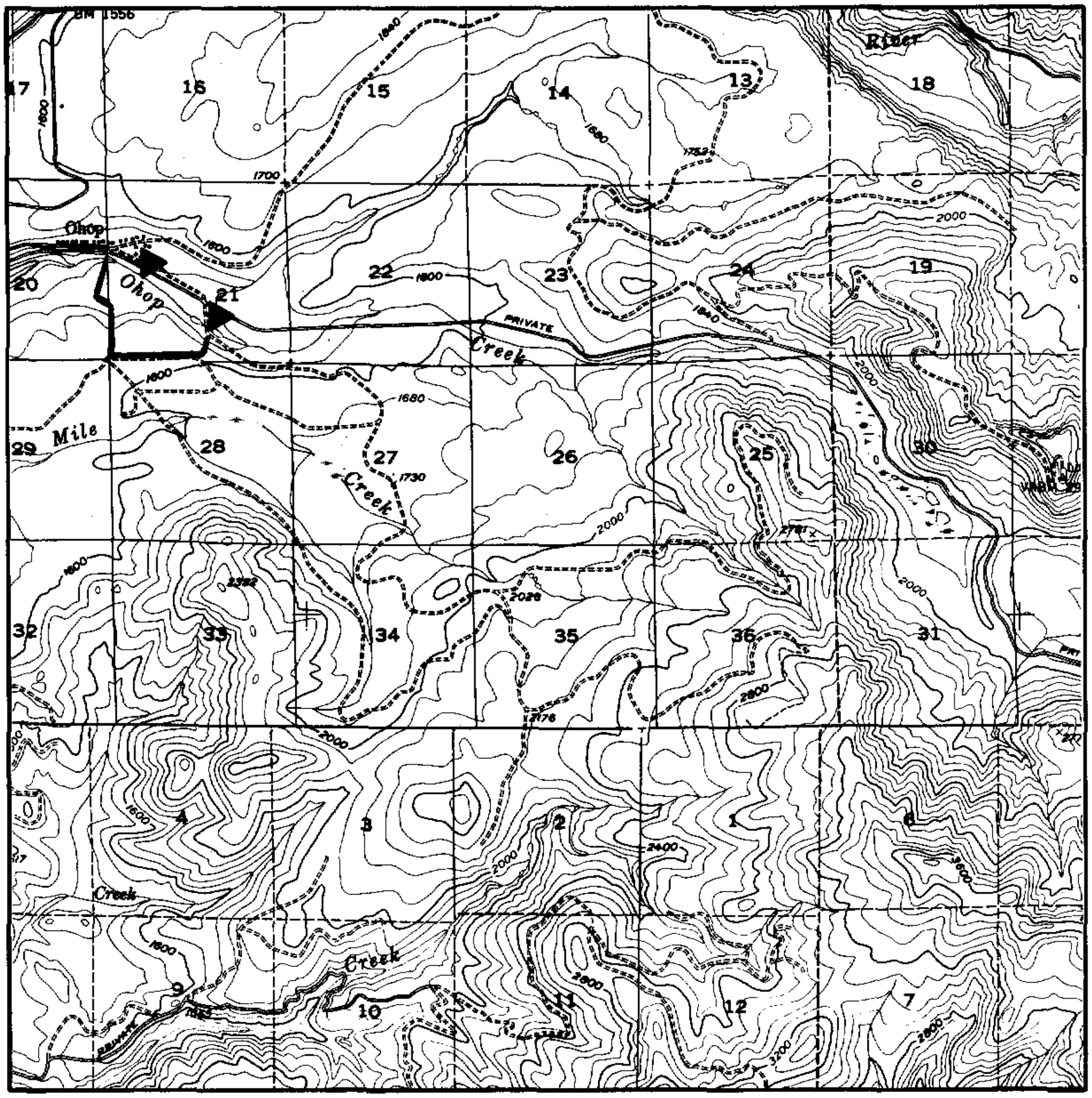
DRY BED LAKES
QUADRANGLE

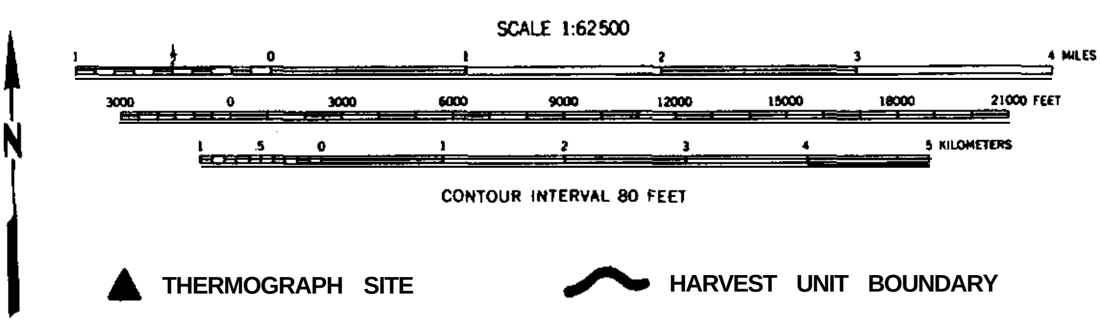
▲ THERMOGRAPH SITE

HARVEST UNIT BOUNDARY

T/F/W TEMPERATURE BMP EVALUATION PROJECT
1990 STUDY SITE

W5: SOUTH FORK OHOP CREEK



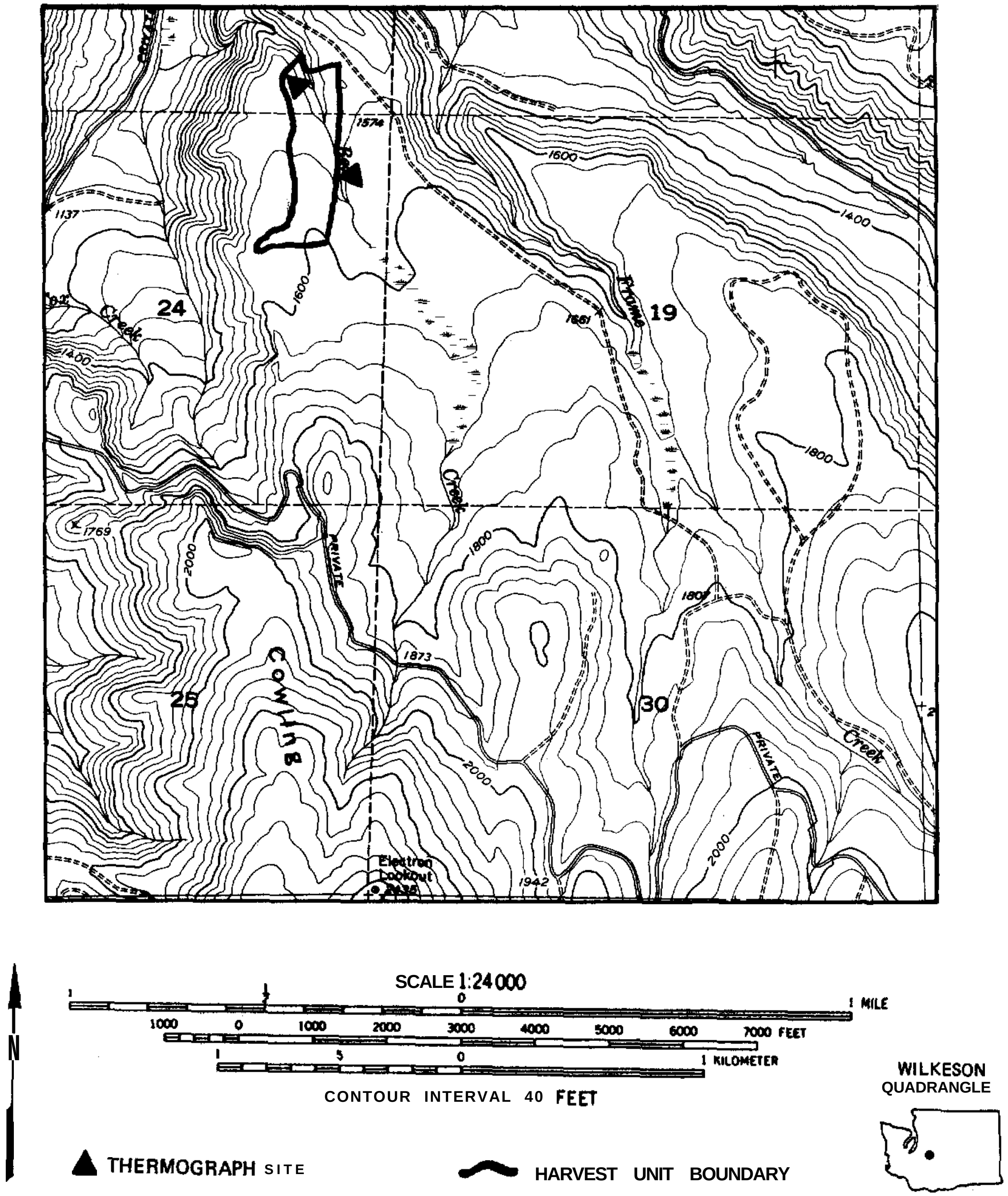


KAPOWSIN
QUADRANGLE

THERMOGRAPH SITE HARVEST UNIT BOUNDARY

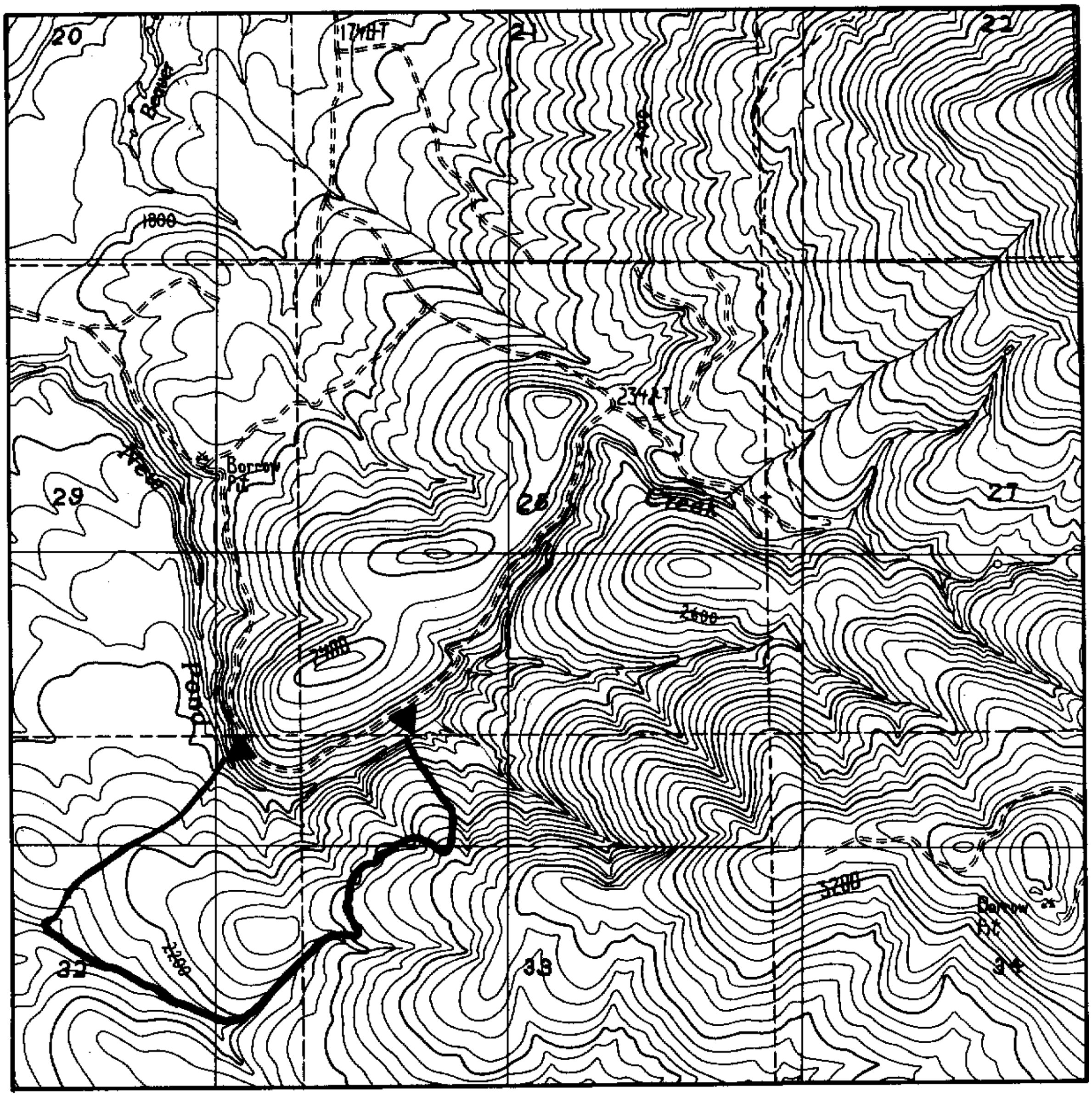
T/F/W TEMPERATURE BMP EVALUATION PROJECT
1990 STUDY SITE

W6: BEAR CREEK



T/F/W TEMPERATURE BMP EVALUATION PROJECT
1990 STUDY SITE

W7: NEW POND CREEK



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1 0 1 KILOMETER

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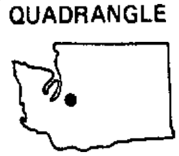
CONTOUR INTERVAL 40 FEET

OLD BALDY MTN QUADRANGLE

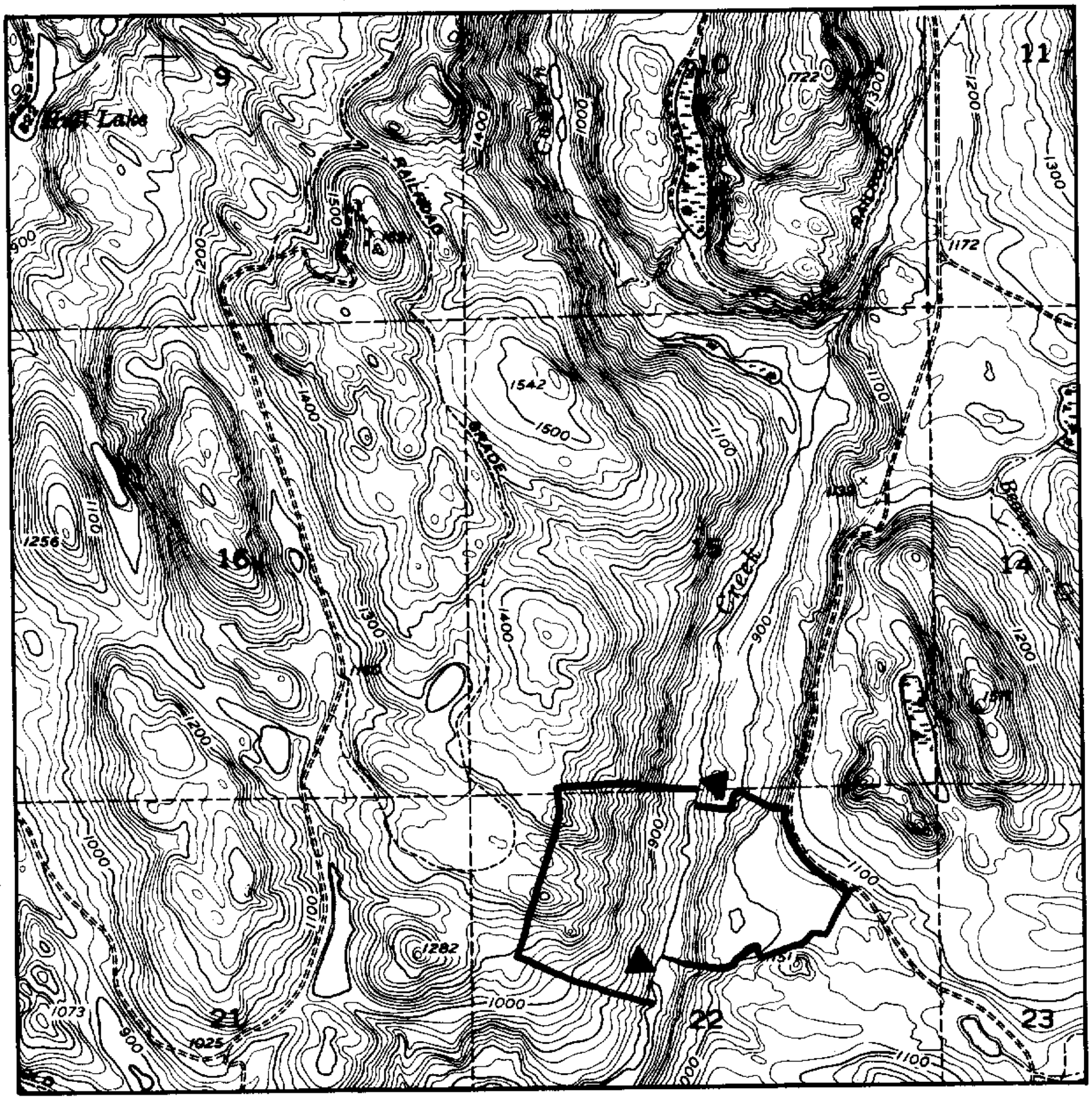


THERMOGRAPH SITE

HARVEST UNIT BOUNDARY

T/F/W TEMPERATURE BMP EVALUATION PROJECT
1990 STUDY SITE

W8: TOKUL CREEK



SCALE 1:24000

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1 .5 0 1 KILOMETER

CONTOUR INTERVAL 20 FEET

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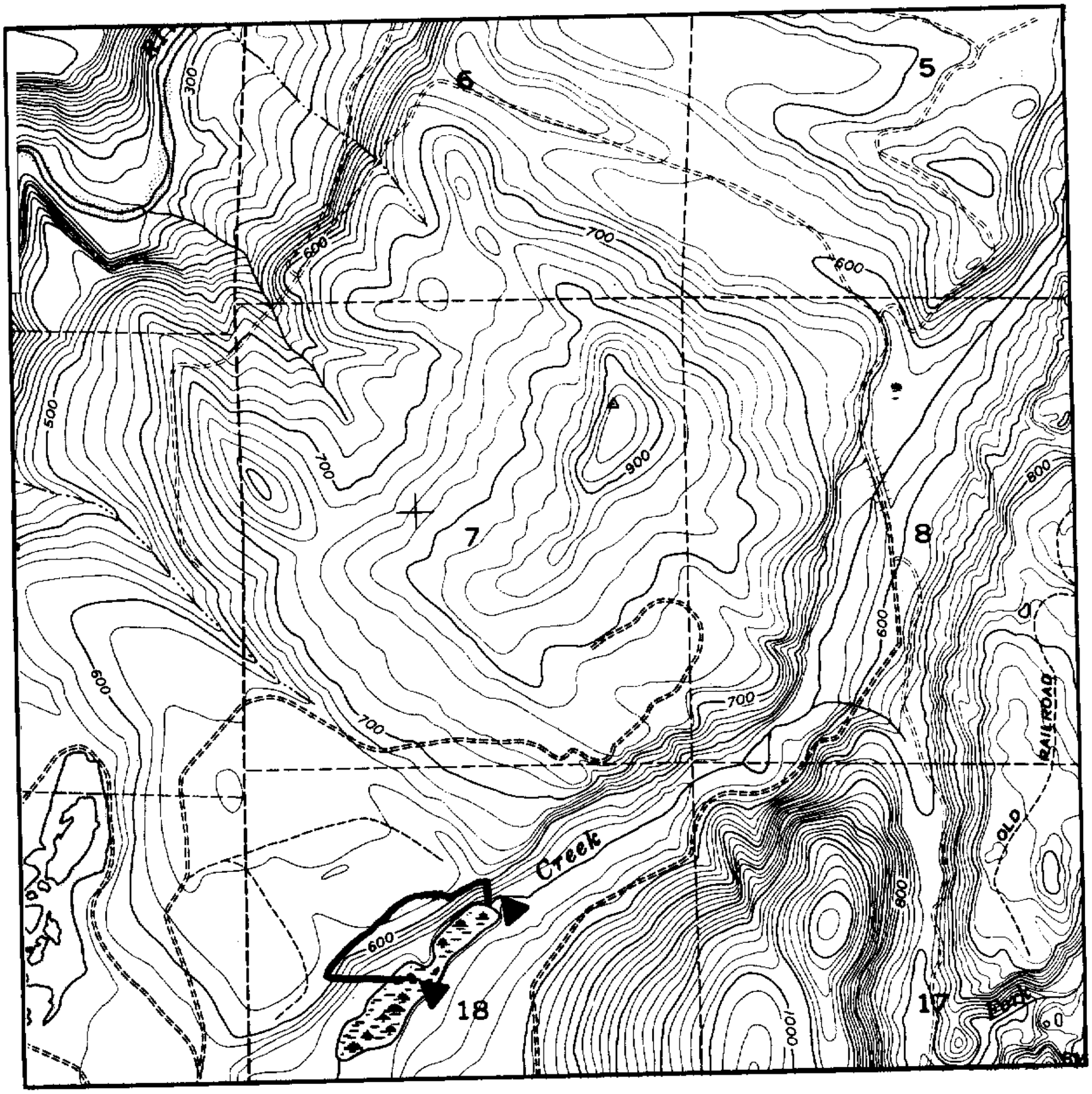
▲ THERMOGRAPH SITE

HARVEST UNIT BOUNDARY

LAKE JOY
QUADRANGLE

T/F/W TEMPERATURE BMP EVALUATION PROJECT
1990 STUDY SITE

W9: GRIFFIN CREEK



SCALE 1:24000

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1 .5 0 1 KILOMETER

CONTOUR INTERVAL 20 FEET

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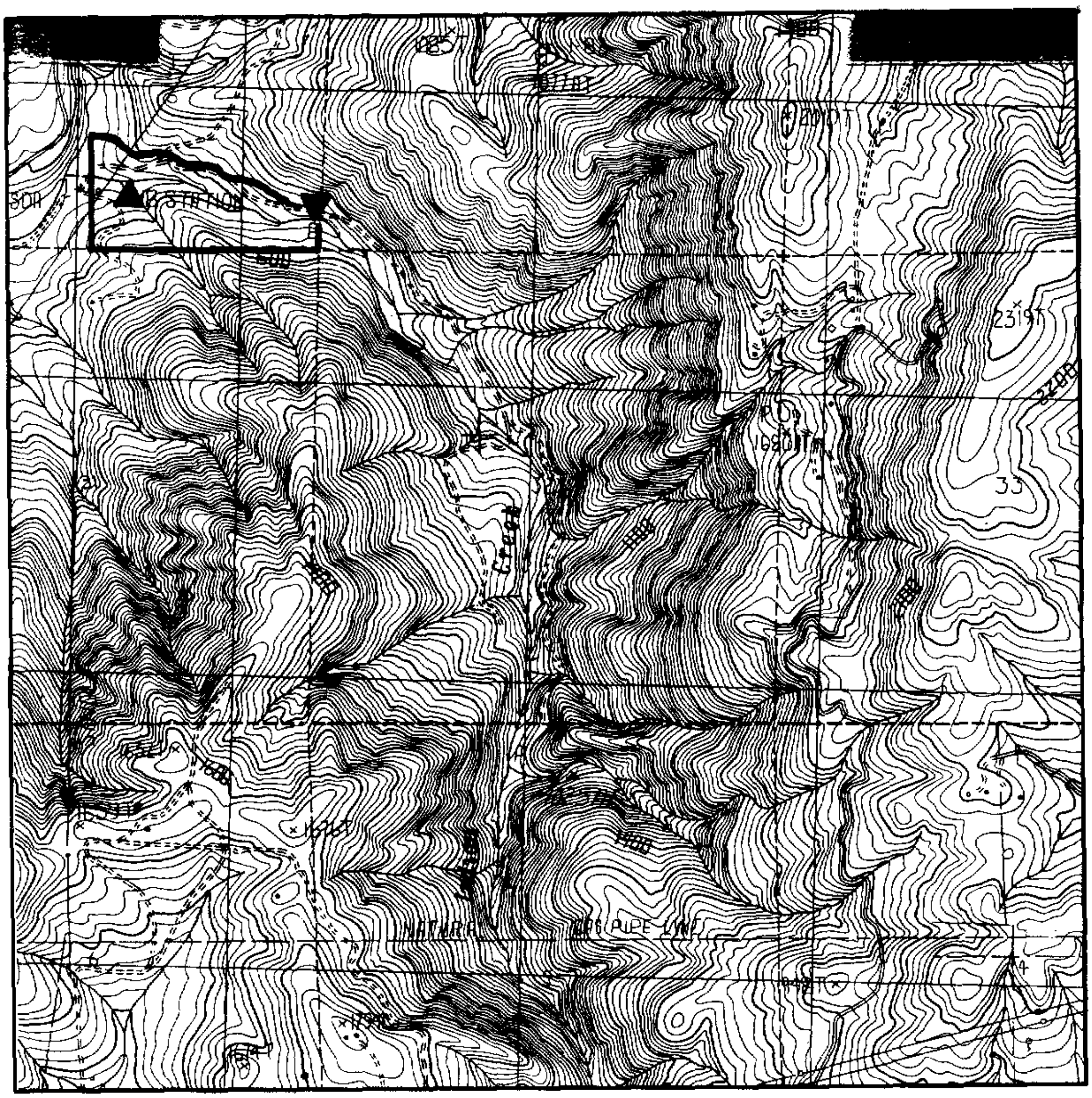
▲ THERMOGRAPH SITE

HARVEST UNIT BOUNDARY

LAKE JOY QUADRANGLE

T/F/W TEMPERATURE BMP EVALUATION PROJECT
1990 STUDY SITE

El: INDIAN CREEK



SCALE 1:24 000

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1 .5 0 1 KILOMETER

CONTOUR INTERVAL 20 FEET

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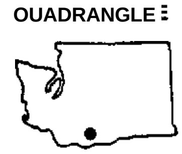
HUSUM QUADRANGLE

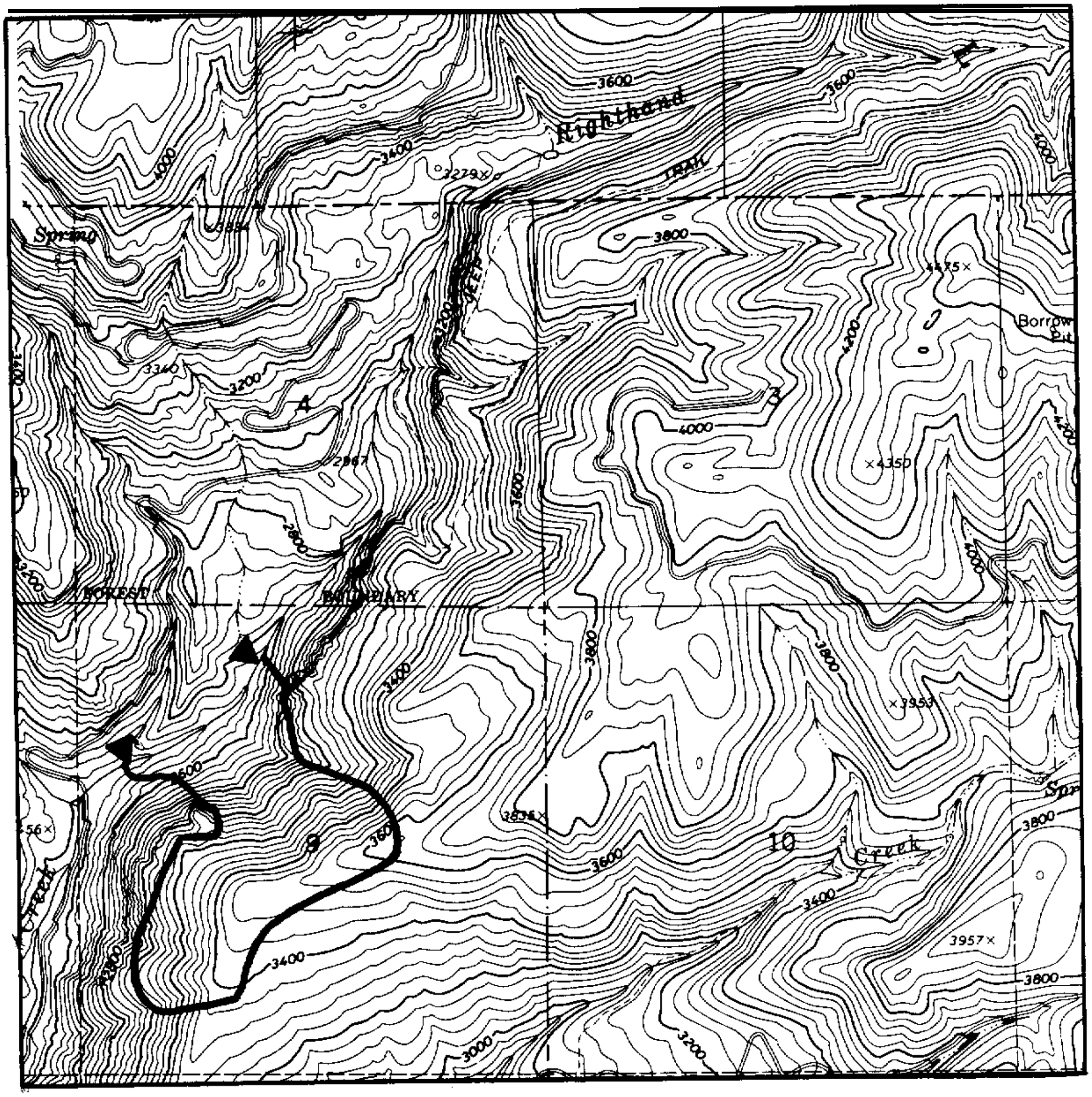


▲ THERMOGRAPH SITE

HARVEST UNIT BOUNDARY

T/F/W TEMPERATURE BMP EVALUATION PROJECT
1990 STUDY SITE

E2: ROCK CREEK.



SCALE 1:24000

1 ½ 0 1 MILE

1000 0 1000 2000 3000 4000 5000 6000 7000 FEET

1 .5 0 1 KILOMETER

CONTOUR INTERVAL 40 FEET

N

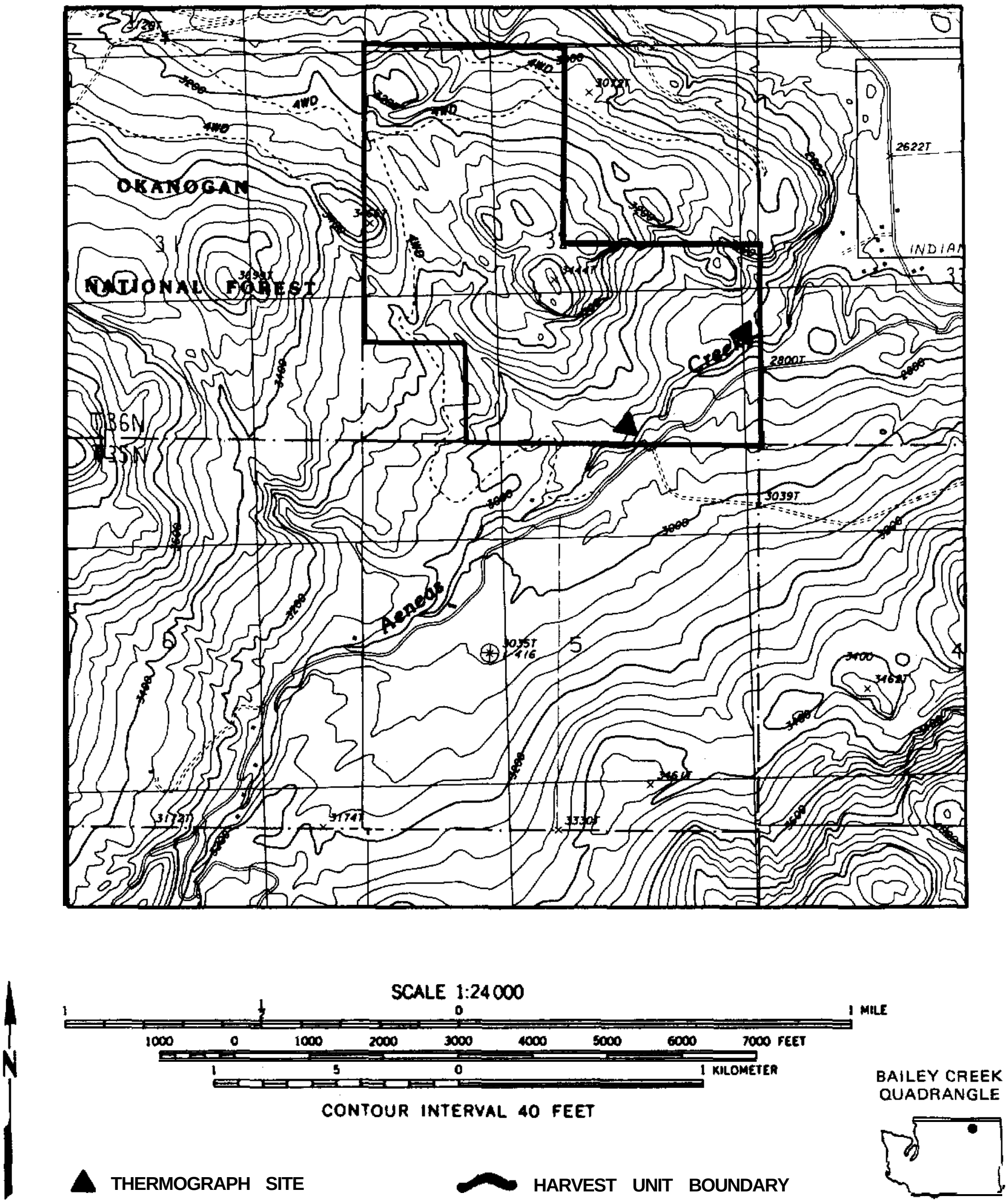
MONASTASH LAKE
QUADRANGLE

▲ THERMOGRAPH SITE

HARVEST UNIT BOUNDARY

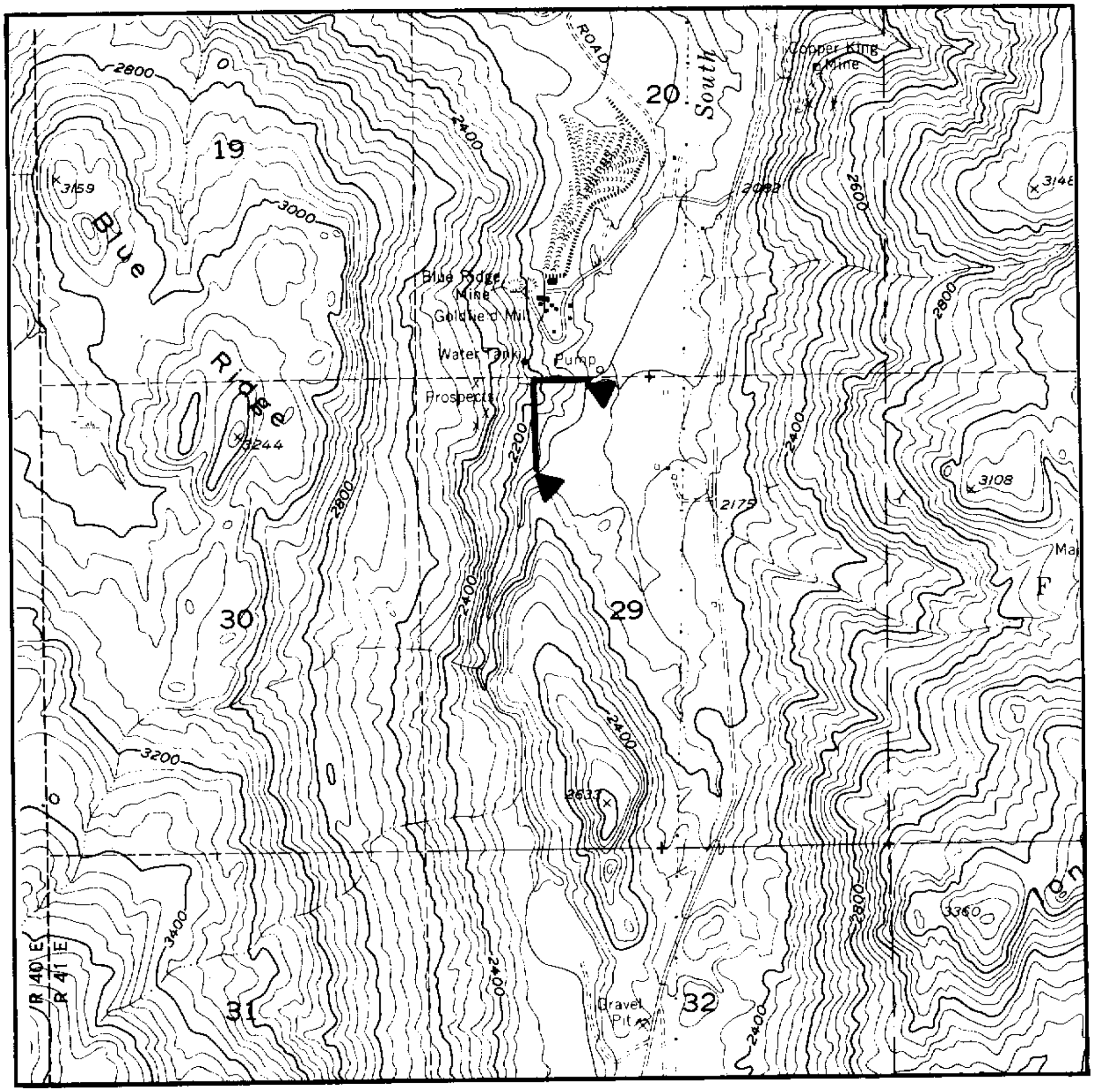
T/F/W TEMPERATURE BMP EVALUATION PROJECT
1990 STUDY SITE

E3: AENEAS CREEK



T/F/W TEMPERATURE BMP EVALUATION PROJECT
1990 STUDY SITE

E4: SOUTH FORK DEEP CREEK



N

SCALE 1:24 000

1 MILE

1000 0 1000 2000 3000 4000 5000 6000 7000 FEET

1 KILOMETER

CONTOUR INTERVAL 40 FEET

SPIRIT
QUADRANGLE

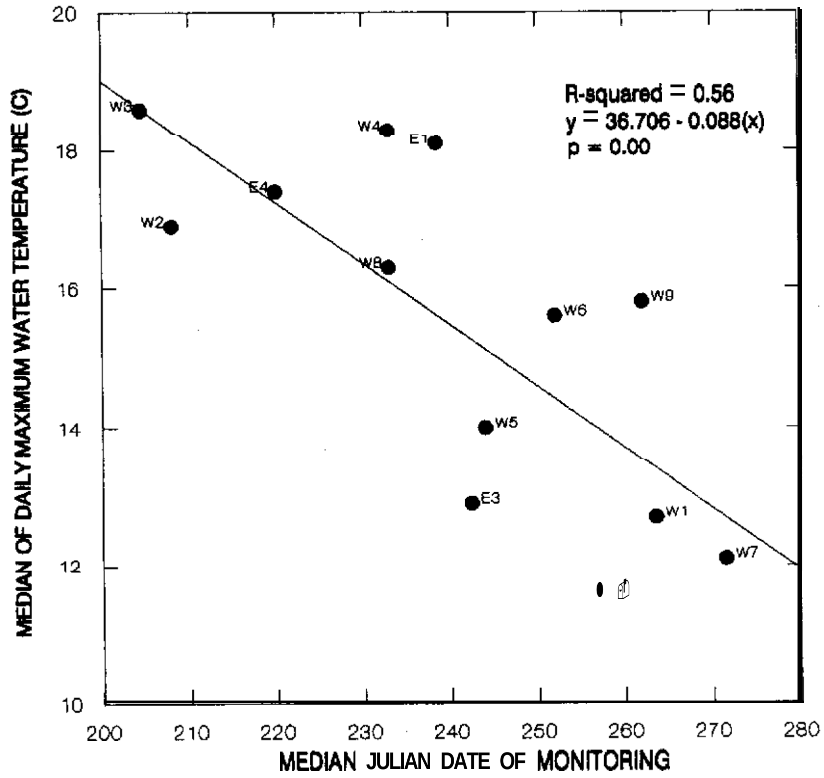
i ▲ THERMOGRAPH SITE

HARVEST UNIT BOUNDARY

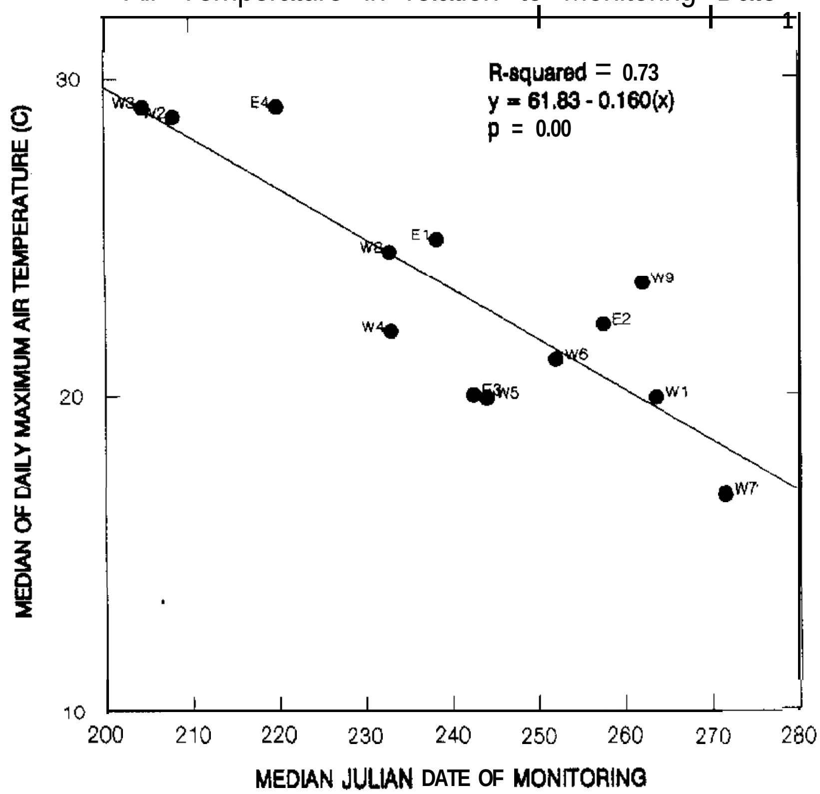
APPENDIX C

SCATTER PLOTS AND REGRESSIONS

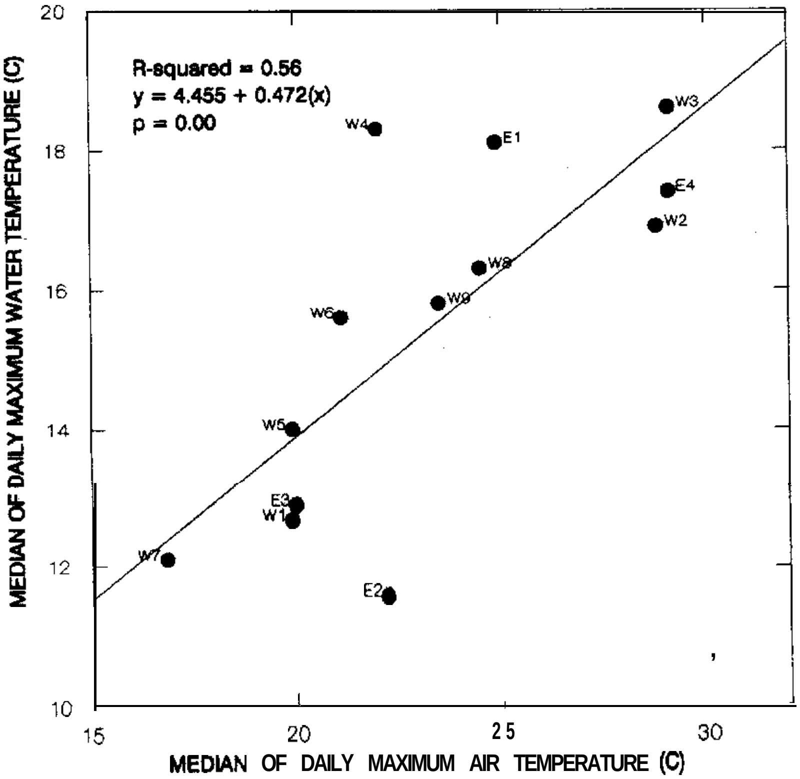
Water Temperature in relation to Monitoring Date



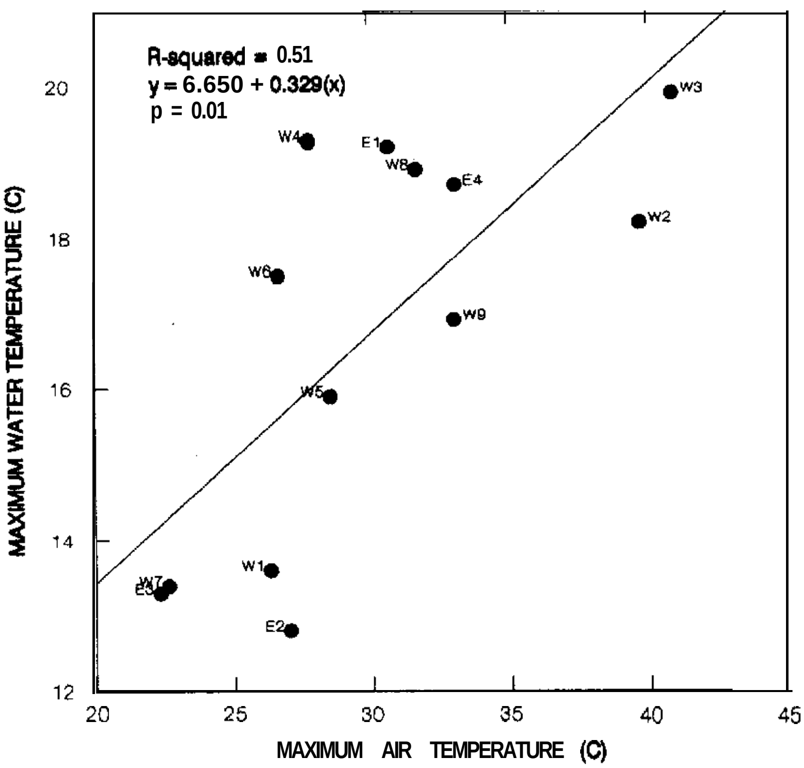
Air Temperature in relation to Monitoring Date



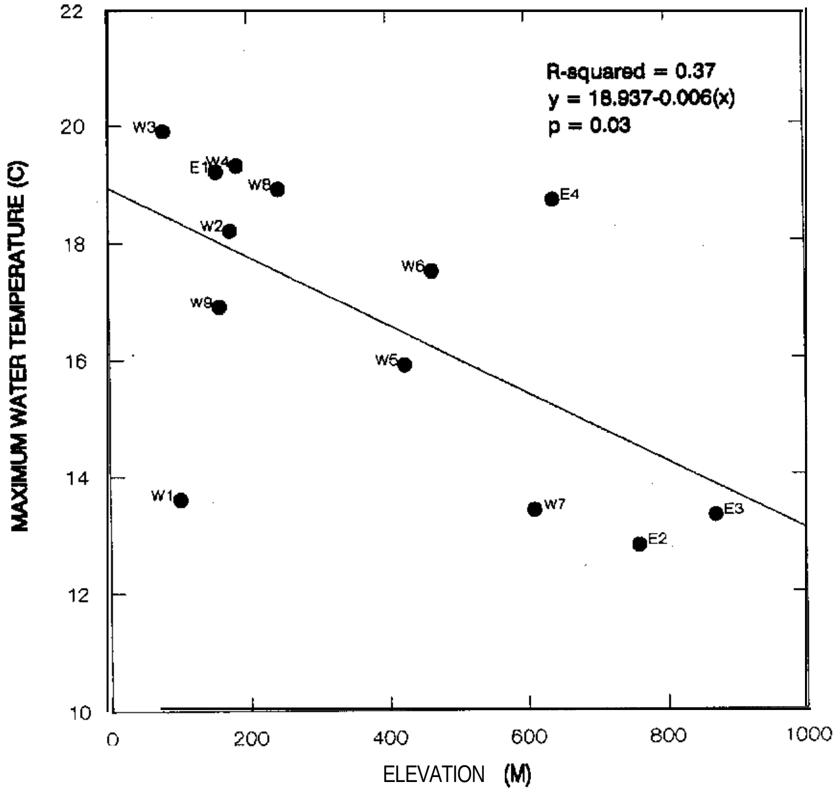
Median Water Temperature in relation to Air Temperature



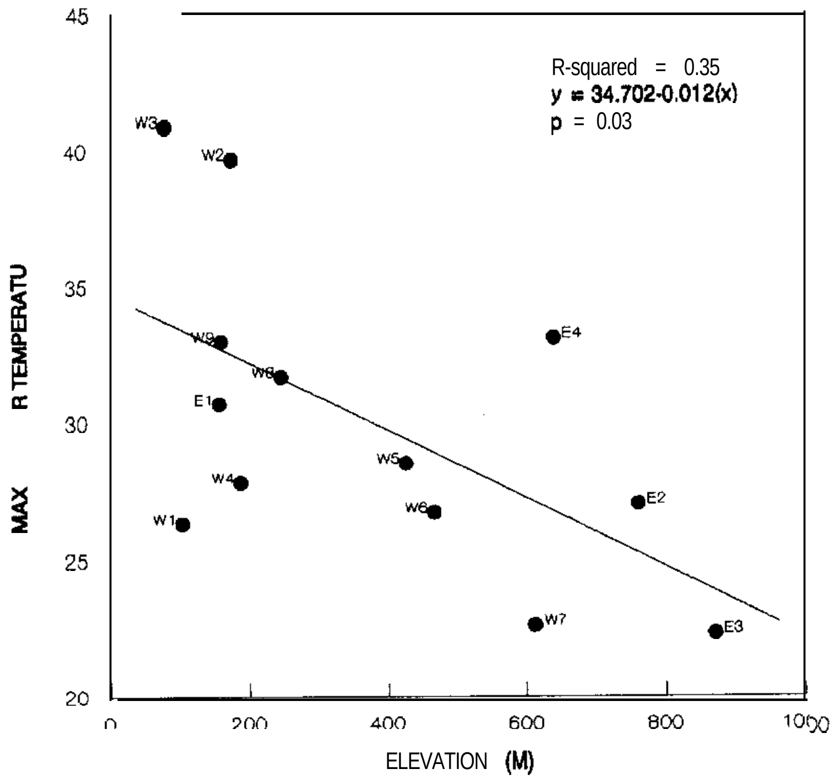
Maximum Water Temperature in relation to Air Temperature



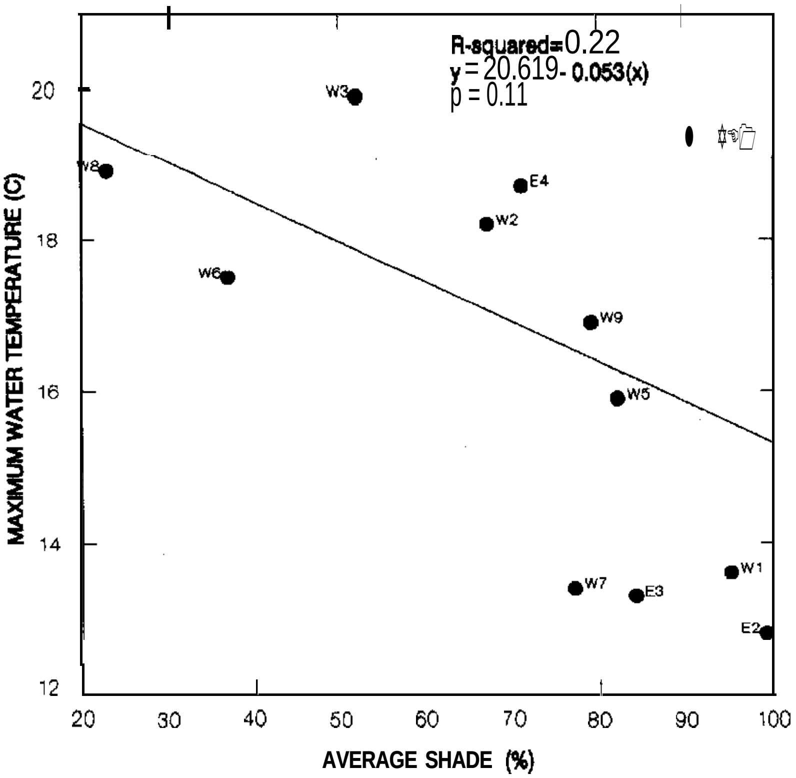
Water Temperature in relation to Elevation



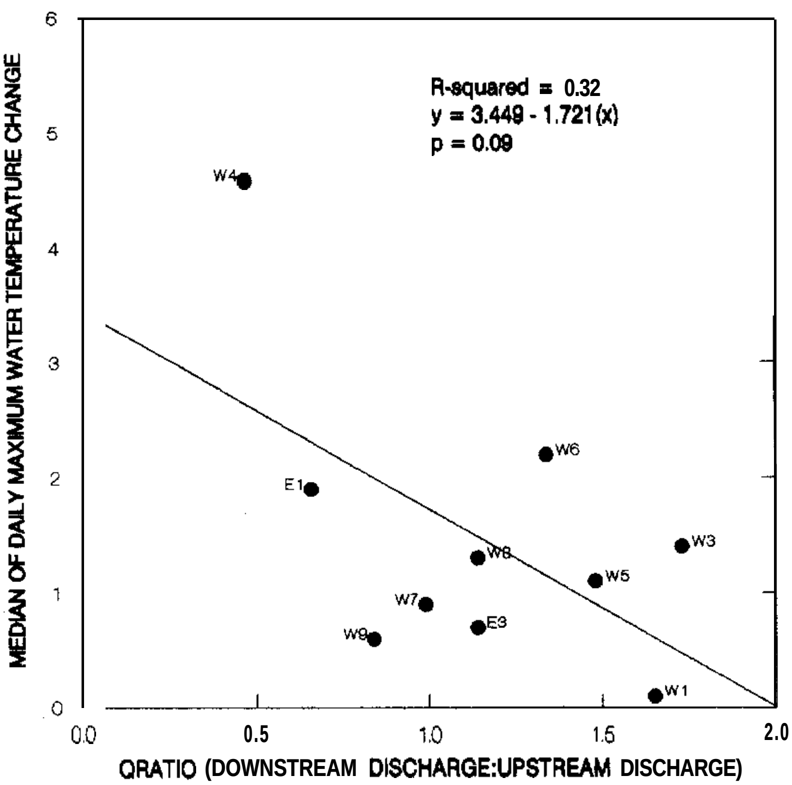
Air Temperature in relation to Elevation



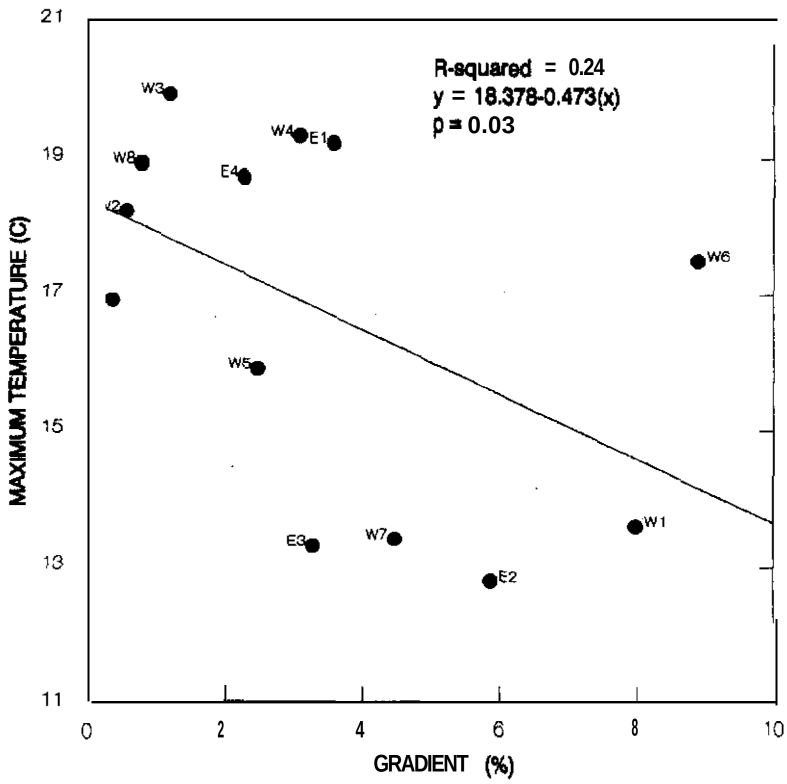
Maximum Water Temperature in relation to Average Shade



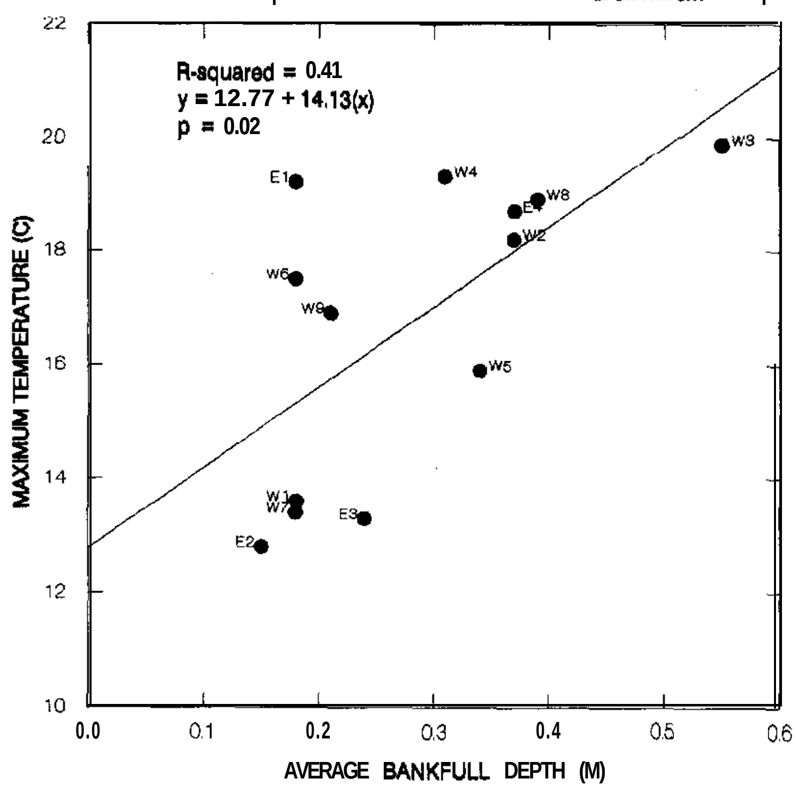
Water Temperature Change in relation to Qratio



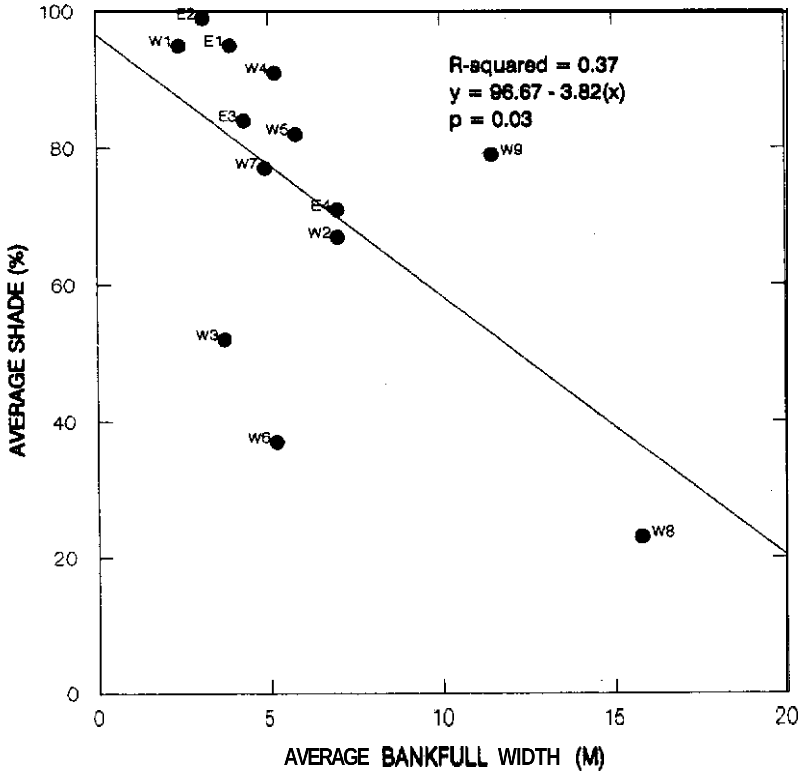
Maximum Temperature in relation to Gradient



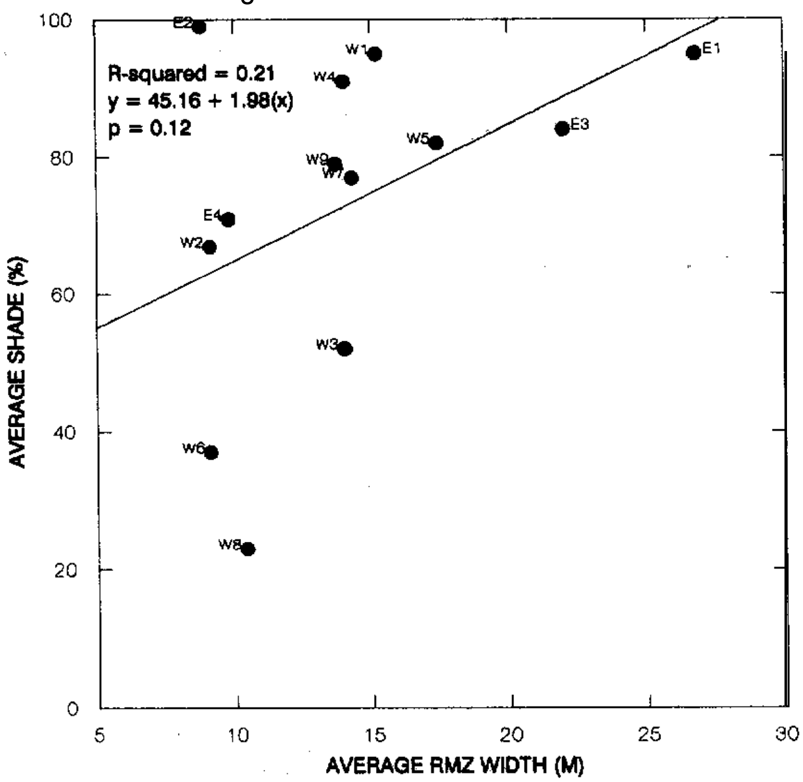
Maximum Temperature in relation to Bankfull Depth



Average Shade in relation to **Bankfull** 'Width



Average Shade in relation to **RMZ** Width



Azimuth Plot: Maximum Water Temperature in relation to Stream Orientation